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VARIABILITY OF MEASURED SONIC BOOM SIGNATURES

VOLUME I - TECHNICAL REPORT

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PREFACE

This report was prepared by McDonnell Douglas Aerospace - West under Task Assignment 10 of contract NAS1 - 19060 with NASA Langley Research Center. This report is organized in two volumes. Volume 1 is the technical report containing a description of the work performed and a discussion of the results. Volume 2 is the data report and contains tabulations of computed metrics of recorded sonic boom.events.

The NASA Technical Monitor for this task was Dr. Kevin P. Shepherd.

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1. INTRODUCTION

A major challenge in the development of a commercial high speed civil Transport is the ability to design the vehicle so that its sonic boom is not objectionable to the community. Human response to sonic boom depends on characteristics of the boom signature. The latter, however, are affected significantly by atmospheric propagation. Since atmospheric conditions can vary in a given day and from day to day, a significant variation in sonic boom signature is possible for a given aircraft design. The impact of this variability in boom signature on perceived human response must therefore be evaluated and understood.

Measurements of sonic boom signatures are often analyzed in terms of maximum overpressure, rise time, and impulse. This type of analysis yields important information about the effects on the boom signature due to propagation through the atmosphere. However, it is difficult to evaluate the effects on the response of people and buildings to sonic booms using these parameters. To alleviate these difficulties an analysis approach based on frequency domain parameters was adopted in the present study.

Using data from two flight test programs conducted at Edwards Air Force Base, California in 1966 and 1987, sonic boom signatures were analyzed in terms of C-weighted sound exposure level (CSEL), A-weighted sound exposure level (ASEL), and Stevens Mark VII perceived level (PLdB), as well as the more traditional peak positive overpressure and rise time. The 1987 database (known as the BOOMFILE database) consists of nearly steady supersonic flyovers of F-4, F-15, F-16, F-18, F-111, T-38, and SR-71 aircraft whereas the 1966 database contains XB-70 flyovers. The variations in sonic boom signatures in these databases were examined as a function of aircraft flight conditions such as altitude, Mach number, and aircraft distance to the side of the microphone. The variability of these sonic boom signatures with respect to atmospheric conditions (based on the time of the day) was determined for both databases. Comparisons were also made with predicted sonic boom signatures, based on propagation through a non-turbulent atmosphere. Sonic boom asymmetry, defined as the difference between the compression portion and the expansion portion of the sonic boom signature (in terms of ΔCSEL, ΔASEL, and ΔPL) was also evaluated.

2. BOOMFILE SONIC BOOM DATABASE

The BOOMFILE database (Reference 1) contains sonic boom signatures recorded from flyovers of F-4, F-15, F-16, F-18, F-111, T-38, and SR-71 aircraft, totaling 43 passes in all. These signatures on the ground were recorded using 13 Boom Event Analyzer Recorder (BEAR) devices on the ground. The 13 BEARs were arranged in a linear array located perpendicular to the flight path at sideline distances ranging from 0 miles (i.e., directly under the flight path) to roughly 20 miles (Figure 1). The aircraft flew across the microphone array with steady flight conditions which were achieved several miles prior to reaching the microphones. BOOMFILE also contains aircraft tracking data which consists of altitude, Mach number, climb angle, acceleration, heading, and lateral and longitudinal position with respect to a reference microphone. This data is provided at one second intervals for most of the aircraft overflights. Limited atmospheric data was also collected during the BOOMFILE tests. This data consists of ground station wind speed and direction, air pressure, and air temperature measured just prior to each set of flyovers. Upper atmosphere rawinsonde data recorded at nearby weather stations on the test days provide wind speed and direction, sound speed, relative humidity, dew point, temperature and pressure at 1,000 foot altitude intervals ranging from roughly 2,500 to 100,000 feet above mean sea level. Additional details about this test program can be found in Reference 1. A listing of the flight conditions of each aircraft run is shown in Table 1.

3. XB-70 SONIC BOOM DATABASE

The XB-70 database (Reference 2) consists of frequency spectra and overpressure time histories of sonic booms for 51 flights of the XB-70 aircraft. The data was collected at several ground stations using a microphone, tuning unit, d.c. amplifier, and FM tape recorder setup played back into a recording oscillograph. The oscillograph plots were then digitized using an optical scanning system. In this test program the microphones were arranged at two sites in different configurations - a four microphone cluster with three ground and one pole (20 feet above the ground) microphones, and an eight microphone cluster with six ground and two pole microphones. Each cluster was located within a 200 foot by 200 foot grid pattern (Figure 2). The location of the measurement site with respect to the aircraft flight path for different runs ranged from directly underneath to a sideline distance of over 15 miles. Each run is considered as one flight over one cluster of 4 or 8 microphones, the flight conditions of which are listed in Table 2. Table III of Reference 2 contains the aircraft altitude, Mach number and sideline distance to the microphone for each run in the XB-70 database. Atmospheric data for this database consists of digitized trace plots for temperature and wind speed parallel and perpendicular to the flight path for all runs. Also included in the database are rawinsonde data consisting of pressure, temperature, wind, and relative humidity recorded at 12:00 and 24:00 hours. Test site climatological data consists of temperature, wind speed and direction, cloud cover description, and dew point within an hour of each run.

4. AUGMENTED SONIC BOOM DATABASE

Both time domain and frequency domain metrics were calculated for each sonic boom signature. The maximum and minimum overpressure, unweighted sound exposure level (SEL), C-weighted sound exposure level (CSEL), A-weighted sound exposure level (ASEL), and perceived loudness level (PLdB) were calculated for each run in both the BOOMFILE and XB-70 databases from the overpressure time histories. This was done by using the classical Fourier transform procedure to obtain the spectrum then applying the appropriate frequency weighting for CSEL and ASEL, or performing Stevens MARK VII procedure for PLdB. Four classifications of rise times, time to 100% P_{max}, time from 10% to 90% P_{max}, time to 75% P_{max}, and time to 50% P_{max} were also calculated. These calculated quantities were added to the BOOMFILE and XB-70 databases resulting in the corresponding augmented sonic boom databases. The database augmentation is done in two parts - one for the noise metrics and one for the rise time. A sample of this augmented database for the BOOMFILE is shown in Table 3a (for noise metrics) and in Table 3b (for rise times). The entire listing of these tables and similar tables for the XB-70 database are included in Appendix A (in volume II of this report).

5. SONIC BOOM SIGNATURE PREDICTION

Sonic boom prediction can, in general, be described as a three step process: prediction of the pressure disturbance in the vicinity of the vehicle, calculation of linear acoustic propagation to large distances accounting for atmospheric gradients, and calculation of non-linear steepening of the boom signature as it propagates. In this study sonic boom signatures were predicted using Carlson's simplified method (Reference 3) option of the sonic boom analysis program MDBOOM (Reference 4). The near field pressure distribution is calculated directly using a simple F-function scaled to local flight and atmospheric conditions. The scaling factors used are the lift parameter (K_L) determined from the aircraft Mach number (M), weight (W), length (l), and local pressure (P_v), and the shape parameter (K_S) determined from the aircraft type and K_L (Figure 3).

K_S is then used to scale the simple F-function of Figure 3 by the factor shown. The signature is propagated to the microphone (far field), resulting in a change of amplitude. An aging or steepening calculation is then performed to model the evolution of the signature into a shock wave. The shock structure of the propagated signature is modeled with the following equations prior to calculating the various noise metrics.

$$p(t) = \frac{\Delta p}{2}\left[1 + \tanh\frac{t}{\Gamma}\right]$$

$$\Gamma = \frac{0.003}{\Delta p}$$

where:

Δp = shock pressure jump (psf)

t = time (sec)

Γ = Empirically determined rise time constant (sec)

The result is a model of a fully aged sonic boom signature propagated through a non-turbulent atmosphere (ideal N-wave).

6. BOOMFILE DATA ANALYSIS

The BOOMFILE data was divided into four groups based on aircraft altitude and Mach number. The range of flight conditions for these groups are shown in Table 4a. The overpressure, rise time, and response metrics of the measured sonic boom signatures for all sideline distances were compared with the corresponding predicted values. Figures 4a and 4b compare the measured maximum overpressure values with predictions for two flight groups. For the low altitude / low Mach number group (Figure 4a), the measured overpressures show a large variability (about a mean value) at all sideline distances. By comparison, the predictions for a non-turbulent atmosphere have a much smaller spread. The high altitude / high Mach number group, however, does not show much variability in the measured data compared to the prediction. While the measurements of both groups include the effects of propagation through the turbulent layer (the last few thousand feet of the atmosphere), the high altitude / high Mach number group has steeper ray paths which results in shorter propagation distances through the lower layer yielding less turbulence distortion. In a recent study, Sparrow and Gionfriddo (Reference 5) have also noted a strong linear correlation between sonic boom waveform distortion and the path length through the turbulence. One factor which may have contributed to the greater variability in the low altitude/ low Mach number group is that this group included 13 flights spread over 5 days whereas the high altitude / high Mach number group included only 2 flights on the same day. Another factor is that some of the measurements in the low altitude / low Mach number group were close to the lateral cutoff distance. These factors can all be expected to increase variability in measurements and reduce theory - data agreement. Similar plots for the two intermediate altitude / Mach number groups which also show greater variability than the high altitude / high Mach number group can be found in Volume II, Appendix B.

The variability in the rise times (defined as the time required to go from 10% to 90% maximum positive overpressure) for the two groups of measurements corresponding to Figures 4a and 4b is plotted in Figures 5a and 5b. Again, the low altitude / low Mach number group shows a wider range of rise time values (up to 50.3 msec) compared to the smaller variation (up to 11.8 msec) for the high altitude / high Mach number group. It is noted that the rise times in the low altitude / low Mach number group are generally significantly higher and rarely significantly lower than prediction. The predicted values, based on a best fit of experimental data (Reference 4), have little variability in both groups of data. A general trend of slightly increasing rise time with sideline distance for measured and predicted data can also be seen.

Loudness level is affected by both overpressure and rise time. Because the high altitude / high Mach number group had good agreement between measured and predicted overpressures and rise times, a similar trend can be expected for the loudness level. This is shown in Figure 6b. For the low altitude / low Mach number group the loudness level of the measured booms have greater scatter (up to 25 PLdB) around the predicted boom loudness level (Figure 6a). It is noted that the loudness level of the measured boom is more frequently lower than the predicted loudness level. For other frequency domain metrics (SEL, CSEL, and ASEL) similar trends were noted. Volume II, Appendix B contains comparison plots for all BOOMFILE and XB70 database groups.

The BOOMFILE database contains four pairs of repeat flights, that is flights of the same aircraft at nearly the same altitude and Mach number. These include F16 at 14000 ft, F4 at 29000 ft, F18 at 30000 ft, and F15 at 45000 ft. Each pair of flights occurred on the same day. The time between flight pairs was roughly 10 minutes for the F16 and F4, 20 minutes for the F15 and 2.5 hours the F18. Figures 7a - 7d, 8a - 8d, and 9a - 9d show a comparison of the measured (and predicted) maximum overpressures, rise times, and loudness level, respectively for the four data pairs. Again, the measured maximum overpressures, rise times, and loudness levels show greater variation for the low altitude (14,000 ft) F16 flights than for the higher altitude F4 (29,000 ft), F18 (30,000 ft), and F15 (45,000 ft) flights. These plots show that even for repeat flights on the same day, the variability in sonic boom measurements due to atmospheric propagation effects is substantial. The general trend of decreasing overpressure, slightly increasing rise time, and decreasing loudness level with sideline distance is also noted.

7. XB-70 DATA ANALYSIS

The XB-70 database represents one of the largest single aircraft sonic boom measurements database. The flight times ranged from 7 AM to 4 PM and since early mornings are associated with low turbulence and afternoons with moderate to high turbulence, this database can be used to quantify the variability in sonic boom measurements due to atmospheric propagation effects by analyzing the data as a function of the time of the day.

The XB-70 database does not contain any data for supersonic flights at altitudes below 30,000 feet. Thus it was not possible to evaluate sonic boom variability at low altitudes versus high altitudes. Repeat runs were identified for nominal operating conditions of 1.8 Mach, 50,000 feet altitude and 2.9 Mach, 70,000 feet altitude. However, the repeat flights within each group were at different sideline distances. The XB-70 database was divided into four altitude / Mach number groups which included all available data (30,000 feet to 72,000 feet altitudes). These groups are shown Table 4b.

The measurements in the XB-70 database used either three or six microphones set up in a 200 by 200 foot square on the ground. Only minor variations are expected from one microphone to the other when they are located in such close proximity to each other. Atmospheric turbulence and thus the signatures are, however, expected to vary with the time of the day. Figures 10a through 10c examine the variation in maximum overpressure, rise time, and loudness level (PLdB) with time of day. The data points are for flight conditions Mach = 1.17 to 1.87 and altitude = 40,000 ft to 50,000 ft (identified as Group 2 in Table 4). The variation in values from one cluster (group of measured data at a given time from the same flight) to another is due to differences in operating conditions and sideline distances. For example, a 7:50 flight with a Mach number of 1.8, altitude of 44,900 feet, and lateral distance of 41,700 feet has a mean value of 2.045 psf, whereas an 15:32 flight with a Mach number of 1.17, altitude of 41,000 feet, and lateral distance of 6,830 feet has a mean value of 3.85 psf. Multiple values of predicted overpressure (Figure 10a) and loudness level (Figure 10c) at a given time represent different operating conditions and sideline distances. It is noted that all predicted values of rise time, although not shown in Figure 10b, varied only from 4 to 8 milliseconds. The variations observed within a cluster of measurements are then due only to propagation effects, presumably turbulence.

It can be noticed in Figure 10a that the variability within a cluster of maximum overpressure is very small for morning flights (prior to 11AM). Around noon and in the afternoon this variability increases a little. The rise time (Figure 10b), shows an increase in variability in the afternoon. Figure 10c shows that variations of as much as 10 PLdB occurred in loudness of booms measured both in the morning and in the afternoon. Similar variability in loudness level was noticed in groups 1,3, and 4 of the XB-70 database with the higher altitude runs generally having slightly lower variability (see Volume II, Appendix B).

8. ASYMMETRY

In the prediction of sonic booms symmetry is assumed for the ideal N-wave. The measure of sonic boom asymmetry was determined by the difference between overpressure, CSEL, ASEL, or PLdB calculated separately for the compression portion and the expansion portion of the sonic boom signature. Variation of these boom asymmetry metrics with the time of day is plotted in Figures 11 and 12. The variability in Δ overpressure (compression minus expansion) for the lower altitude group of flights (Figure 11a) is slightly greater than the high altitude group of flights (Figure 11b). The lower values and smaller variability in Δ overpressure for the higher altitude group is consistent with the near perfect N-wave (Δ overpressure equals zero) shaped signatures and steeper propagation ray paths associated with the signatures of this altitude group. In the "afternoon hours", the asymmetry in loudness level (Figure 12) has a greater variability than the asymmetry in overpressure. This is an indication of the larger effect of atmospheric turbulence on sonic boom rise time. Also note in Figure 12b that the loudness level of the compression portion of the sonic boom signature is generally lower than the loudness level of the expansion portion. This is an indication that atmospheric propagation affects the front shock more than the aft shock. Volume II, Appendix C contains additional asymmetry data.

9. STATISTICAL ANALYSIS

The forgoing analysis has indicated that variability in sonic boom rise time increases with sideline distance (Figure 8) and during afternoon hours (Figure 10b). In order to separate these effects, the XB-70 database was divided into two data groups based on lateral cutoff distance calculated from the cutoff azimuth angle, as determined using the MDBOOM program (Reference 4). The two groups were data falling inside 50 percent of the calculated lateral cutoff distance (dyc) and that which fell outside of this boundary. Such a grouping has been used in Reference 6 in the analysis of BOOMFILE data. The histograms in Figures 13a and 13b represent the distribution of measured maximum overpressure values, normalized by the corresponding calculated (standard non-turbulent atmosphere) maximum overpressure for these two groups in the XB-70 database. It can be seen that for the below 50% dyc group maximum overpressure distribution is approximately symmetrical. This is statistically representative because of the large number of events (180). By comparison, the above 50% dyc group shows a large variability in measured maximum overpressure. The corresponding loudness level variability is plotted in Figure 14. Again it can be seen that the below 50% dyc group (Figure 14a) has a symmetrical PL_{meas} distribution with a -0.15 dB mean for PL_{meas} - PL_{calc} / P_{max} whereas the above 50% dyc group (Figure 14b) has a bi-modal type distribution with a -1.7 dB mean and larger variance about the mean. The range of altitudes and Mach number of both groups is large to include all points in the database. Other statistical measures such as variance, skewness, and kurtosis are shown on the figures as well.

The variability of measured maximum overpressure in the below 50% dyc group was further analyzed in terms of the time of day in order to quantify the turbulence effects. The histogram in Figure 15a shows that the maximum overpressure measurements for the morning (before noon) flights have a smaller variance (0.07) than for flights which occur after noon (0.11) as shown in Figure 15b. While the mean values of maximum overpressure in the two plots are not very different, the mean values occur more frequently before noon than after noon. Figures 16a and 16b present the data of Figure 15 in terms of loudness level. Again, the increased variance in the afternoon flights (28.57 opposed to 15.26) can be noticed as a broad and rather flat histogram. The mean value is essentially independent of time-of-day. This trend was also observed in the sonic boom measurement program at White Sands Missile Range (Reference 7).

Attempts were made to classify each run based on the degree of turbulence calculated from the atmospheric data of the BOOMFILE and XB-70 databases. A procedure for calculating the Richardson number, outlined in Reference 8 (pp. 141 - 143), from the rawinsonde wind and temperature profiles of BOOMFILE was used. The profiles, however, did not include measurements at altitudes and times corresponding to the ground station data to allow meaningful calculations. The Richardson numbers calculated using the XB-70 database were also erroneous, not surprising because the rawinsonde data was taken at locations which were up to 15 miles away and only down to altitudes of around 1,200 feet. Because the Richardson number is a surface layer parameter, other turbulence structure parameters associated with the mixing layer like stability ratio and refractivity index were also calculated. Unfortunately, the atmospheric data provided was again not adequate to allow valid calculations.

The XB-70 data was also analyzed in terms of equivalent (average) overpressures and equivalent (logarithmic average) PLdB because the measurements used a cluster of nearly collocated microphones. In this analysis the average maximum overpressure and the logarithmic average PLdB as well as their respective standard deviations were calculated for each cluster of microphones, including only the ground microphones. These equivalent parameters also show the trend of increased variability with decreasing altitude/Mach number (see Volume II, Appendix D).

10. CONCLUSIONS

The BOOMFILE and XB-70 sonic boom databases were analyzed in terms of overpressure and rise time as well as frequency dependent parameters such as perceived loudness level, ASEL, and CSEL in order to quantify the effects on sonic boom signature due to propagation through atmosphere. Each database was first divided into four groups according to flight altitude and Mach number. This analysis indicated that for the lower aircraft altitude and lower Mach number runs the propagation through atmosphere causes large variations in the measured sonic boom metrics, up to 5.6 psf in overpressure, 50.3 milliseconds in rise time, and 27 PLdB. This may be attributed to the fact that the higher Mach number flights have steeper ray paths and therefore reduced effects of refraction. A steep ray path will also result in less distance traveled through the earth's lower boundary layer and thereby reduce the effects of propagation through turbulence. Another contributing factor is that the lower altitude / Mach number runs, in some cases were close to lateral cutoff. A third factor, which pertains to the BOOMFILE data only, is that the lower altitude / Mach number groups included many flights over several days, whereas the two high altitude / Mach number flights occurred on the same day, i.e. no day to day variation. A general trend of decreasing overpressure, increasing rise time, and decreasing perceived loudness level with lateral distance was seen as well.

The variability in overpressure and rise time tended to be less in the early morning increasing in the afternoon. Variations in loudness level up to 10 dB were observed in both afternoon and morning flights. The asymmetry of the measured sonic boom signatures was defined as the difference in overpressure (or loudness level) between the front compression part of the signature and the aft expansion part of the signature. The variability in these asymmetry measures (Δoverpressure and Δloudness level) as a function of time of day was also evaluated. The variability in Δloudness level again exceeded that of Δoverpressure, an indication of the influence turbulence has on rise time.

A statistical analysis of the XB-70 data showed that for data within 50% of the lateral cutoff distance the measured sonic boom metrics had a normal distribution, whereas for data beyond 50% lateral cutoff distance a bi-modal distribution and greater variability were observed. Time of day analysis of the normal distribution data showed that the mean value occurred more frequently in the morning than the afternoon, but that the value itself was independent of the time of day. This is clear evidence of increased turbulence in the afternoon.

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Table 1 - BOOMFILE Flight Conditions Summary

DATE	AIRCRAFT	FLIGHT TRACK INTERSECTION	MACH NUMBER	ALTITUDE (Ft MSL)	BOOM AT SITE 00 (Local Time)
31 JUL 87	F-4 *	57.8	1.20	16000	08:41:20
03 AUG 87	F-4	60.1	1.24	29200	07:48:33
	F-4	60.6	1.29	29300	07:58:33
	F-4	53.6	1.10	13000	08:08:04
	F-4	59.2	1.10	14400	10:29:59
	F-4	61.3	1.37	44400	10:43:22
	T-38	58.6	1.00	13600	10:05:35
	T-38	56.0	1.10	13000	10:12:15
	T-38	59.5	1.11	29600	12:28:18
	T-38	60.5	1.05	21200	12:38:17
04 AUG 87	AT-38	60.0	1.17	41400	07:19:41
	AT-38	60.0	1.12	32300	07:30:09
	AT-38	63.0	1.15	16700	07:36:46
	AT-38	59.6	1.20	30300	09:14:06
	AT-38	59.0	1.10	14000	09:23:15
	F-15	61.5	1.38	41400	07:56:42
	F-15	60.3	1.20	29700	08:04:06
	F-15	60.6	1.10	12500	08:10:13
	F-15	60.0	1.13	15200	10:46:15
	F-15	59.0	1.28	31000	11:02:18
	F-15	64.0	1.42	45000	11:11:28
	F-15	60.0	1.40	45500	11:34:21
05 AUG 87	F-16	57.0	1.25	29500	09:06:05
	F-16	60.0	1.43	46700	09:33:54
	F-16	58.8	1.17	19300	09:44:51
	F-16	59.5	1.13	14400	11:44:24
	F-16	60.6	1.12	13800	11:54:39
	F-16	60.5	1.25	30000	12:04:46
	SR-71	60.8	2.50	64800	09:26:12
	SR-71 *	59.8	3.00	73000	10:55:12
	SR-71	59.4	1.23	32400	11:08:38
	SR-71	62.0	1.70	52000	12:35:51
06 AUG 87	F-18	60.0	1.30	30000	07:44:12
	F-18	59.6	1.40	44700	07:57:05
	F-18	58.0	1.10	14200	08:10:36
	F-18	59.8	1.30	30000	10:22:47
	F-18	59.8	1.43	45000	10:34:14
	F-18 *	59.8	1.10	13000	10:48:38
	F-14	56.2	1.20	31500	08:28:45
	F-14	62.0	1.27	16500	10:43:43
	F-111D	59.8	1.20	14000	11:48:18
	F-111D	59.8	1.40	45000	12:04:44
07 AUG 87	F-111D	58.3	1.25	29900	10:50:26

For each of these flights, except where noted by an asterisk, tracking data are provided

Table 2 - XB-70 Flight Conditions Summary

DJM File#	Date	A/C#-Flt #	T/O Time	T/O Gr.Wt.	Flt. Time	Boom Time	Boom Mach	Boom Alt	Boom Gr.Wt.	Land Gr.Wt.
1	3-4-65	1-7	1018	480K	1:37	1114	1.83	50500	337K	297K
2	4-20-65	1-10	1113	510K	1:42	1213	1.80	48000	350K	300K
3	7-1-65	1-14	0650	510K	1:44	0800	2.60	66000	310K	285K
4	7-27-65	1-15	0707	510K	1:43	0732	1.23	32000	423K	300K
5	8-10-65	2-2	0700	470K	1:27	0740	1.38	42300	357K	310K
6	8-18-65	2-3	1220	490K	1:58	1330	1.40	46000	381K	305K
7	8-20-65	2-4	1115	493K	2:04	1159	1.42	42500	387K	295K
8	9-22-65	1-16	1200	510K	1:57	1225	1.50	33800	456K	300K
9	9-29-65	2-6	1147	495K	2:04	1220	1.35	33000	440K	295K
10	10-5-65	2-7	1213	495K	1:40	1243	1.42	31000	438K	295K
11	10-11-65	2-8	1310	515K	1:55	1332	1.51	34000	423K	298K
12	10-14-65	1-17	0906	510K	1:47	0936	1.76	41000	433K	300K
13	10-16-65	2-9	0912	520K	1:43	1027	1.40	50000	313K	295K
14	11-2-65	2-11	1126	520K	1:54	1255	1.80	50500	317K	295K
15	11-4-65	1-18	1019	515K	2:04	1105	1.87	41500	357K	300K
16	11-18-65	1-21	1233	515K	2:02	1338	1.61	41500	348K	300K
17	11-30-65	1-22	0900	515K	1:59	1010	1.82	53000	325K	295K
18	12-1-65	2=13	0902	525K	2:02	1030	2.31	60000	328K	297K
19	12-2-65	1-23	0915	515K	1:59	1040	1.79	54000	317K	300K
20	12-3-65	2-14	0908	520K	1:55	1030	2.48	65500	329K	300K
21	12-10-65	1-25	1230	515K	2:18	1315	1.55	30500	436K	--
			(2nd	run)	----	1400	1.25	38000	371K	295K
22	12-11-65	2-15	0858	520K	2:03	0918	1.50	37000	454K	--
			(2nd	run)	----	1028	2.90	70000	321K	300K
23	12-21-65	2-16	1307	510K	1:49	1427	2.92	70000	321K	300K
24	1-3-66	2-17	0901	520K	1:52	1020	2.91	69800	317K	295K
25	1-11-66	1-31	0702	447K	1:35	0750	1.80	44900	369K	295K
26	1-12-66	2-18	0855	525K	1:48	1018	2.05	66000	297K	290K
27	1-15-66	1-33	1108	450K	1:27	1153	1.78	45100	373K	290K
28	3-4-66	1-36	1055	523K	2:27	1140	1.75	41000	446K	--
	(2nd station-same run)				----	1140	1.82	42000	445K	293K
29	3-7-66	1-37	1402	520K	2:19	1532	1.17	41000	344K	--
	(2nd station-same run)				----	1532	1.17	40000	343K	295K
30	3-15-66	2-24	0909	535K	1:59	1030	2.66	68500	310K	--
	(2nd station-same run)				----	1030	2.66	69300	310K	293K
31	3-17-66	2-25	0847	535K	1:52	1015	2.74	66000	308K	--
	(2nd station-same run)				----	1015	2.74	66000	308K	297K
32	3-19-66	2-26	1040	530K	1:57	1210	2.84	70300	305K	--
	(2nd station-same run)				----	1210	2.84	70300	304K	291K
33	3-28-66	1-40	0950	520K	1:41	1053	1.80	51000	319K	--
	(2nd station-same run)				----	1053	1.80	51000	319K	300K
34	3-29-66	2-29	1027	530K	1:51	1137	1.56	44000	314K	--
	(2nd station-same run)				----	1137	1.56	44000	314K	--
	---------------(2nd run)				----	1152	1.36	36400	304K	--
	(2nd station-2nd run)				----	1152	1.36	36400	304K	300K
35	4-5-66	1-42	1026	520K	2:01	1138	1.55	52000	334K	295K
36	4-21-66	1-45	1539	524K	2:02	1646	2.26	53000	338K	290K
37	4-23-66	2-35	1120	525K	2:01	1140	1.11	32000	468K	--
	(2nd station-same run)				----	1140	1.18	32000	467K	--
	---------------(2nd run)				----	1255	2.20	64000	362K	--
	(2nd station-2nd run)				----	1255	2.20	64000	362K	310K
38	5-16-66	2-38	0900	520K	2:09	1040	1.30	44300	321K	300K
39	5-27-66	2-42	1100	520K	2:08	1240	1.24	39800	310K	300K

Total number of sonic boom flights = 39

Total number of sonic boom runs = 51

Table 3a - Augmented BOOMFILE Database (Noise Metrics)

FILE NAME	Time (Hours)	Pmax (PSF)	Pmin (PSF)	ESEL (dB)	ASEL (dB)	CSEL (dB)	PLDB (dB)	Sideline (Feet)	Altitude (Feet)	Mach #	Aircraft
P00 841 800	8.68	3.491	-3.235	123.700	98.600	114.000	113.600	0.0	16000.0	1.20	F4
P00 748 803	7.80	2.682	-2.008	122.100	91.200	110.400	107.200	1387.0	29200.0	1.24	F4
P00 758 803	7.97	2.929	-2.722	123.400	96.100	112.100	110.900	3751.0	29300.0	1.29	F4
P001029 803	10.48	13.335	-3.232	128.300	109.800	120.500	124.400	-3358.0	14400.0	1.10	F4
P001043 803	10.72	1.764	-1.536	120.200	87.400	106.400	103.200	4754.0	44400.0	1.37	F4
P001238 803	12.63	0.726	-0.597	112.100	77.900	97.400	90.800	3717.0	21200.0	1.05	T38
P00 719 804	7.32	0.493	-0.453	106.900	71.700	95.200	86.500	-597.0	41400.0	1.17	AT38
P00 730 804	7.50	0.529	-0.672	110.200	72.800	95.900	88.400	1033.0	32300.0	1.12	AT38
P00 736 804	7.60	0.613	-0.646	109.300	73.900	98.000	89.500	7079.0	16700.0	1.15	AT38
P00 756 804	7.93	1.489	-1.095	115.600	86.900	104.800	102.400	8703.0	41400.0	1.38	F15
P00 756 804	7.93	0.207	-0.218	106.500	75.200	89.600	85.500	8703.0	41400.0	1.38	F15
P00 8 4 804	8.07	1.905	-1.496	118.900	88.800	107.200	103.900	2928.0	29700.0	1.20	F15
P00 810 804	8.17	3.507	-3.260	125.100	98.400	114.000	113.400	3679.0	12500.0	1.10	F15
P00 914 804	9.23	0.747	-0.817	111.100	79.500	100.100	94.100	-2003.0	30300.0	1.20	AT38
P00 923 804	9.38	1.160	-0.597	110.800	79.200	101.600	95.400	-2403.0	14000.0	1.10	AT38
P00 952 804	9.87	0.482	-0.399	106.500	74.700	94.200	88.500	0.0	0.0	0.00	
P001046 804	10.77	5.851	-3.044	124.100	103.500	116.900	118.600	4288.0	15200.0	1.13	F15
P0011 2 804	11.03	2.168	-1.571	118.700	89.900	108.300	105.500	-2853.0	31000.0	1.28	F15
P001111 804	11.18	0.982	-0.808	113.800	80.500	99.500	95.300	17103.0	45000.0	1.42	F15
P001134 804	11.57	1.924	-0.972	114.800	88.600	106.700	103.900	905.0	45500.0	1.40	F15
P001139 804	11.65	1.593	-1.071	115.400	82.500	105.000	99.400	0.0	0.0	0.00	
P00 820 805	8.33	0.895	-0.545	111.400	78.600	100.400	94.300	0.0	0.0	0.00	
P00 820 805	8.33	0.754	-0.648	112.800	76.700	99.800	92.800	0.0	0.0	0.00	
P00 9 6 805	9.10	1.081	-0.925	113.900	78.100	101.900	94.200	-10561.0	29500.0	1.25	F16
P00 9 6 805	9.10	0.705	-0.491	107.900	76.200	99.600	92.000	-10561.0	29500.0	1.25	F16
P00 926 805	9.43	1.205	-0.958	116.200	88.100	103.100	101.600	4226.0	64800.0	2.50	SR71
P00 933 805	9.55	0.879	-0.871	113.000	79.200	100.400	94.500	-2606.0	46700.0	1.43	F16
P00 944 805	9.73	2.809	-2.448	120.900	92.900	111.900	108.800	-5091.0	19300.0	1.17	F16
P001055 805	10.92	0.827	-0.698	114.500	80.900	97.800	93.200	0.0	73000.0	3.00	SR71
P0011 8 805	11.13	2.262	-1.773	120.700	92.800	107.400	107.300	-2986.0	32400.0	1.23	SR71
P001144 805	11.73	5.628	-3.328	124.600	96.700	116.700	114.500	-2119.0	14400.0	1.13	F16
P001154 805	11.90	3.772	-3.552	124.400	95.300	114.700	112.000	3264.0	13800.0	1.12	F16
P0012 4 805	12.07	1.900	-1.388	116.700	91.400	108.300	106.600	1993.0	30000.0	1.25	F16
P001235 805	12.58	1.330	-0.980	115.900	88.000	104.600	102.500	9995.0	52000.0	1.70	SR71
P00 744 806	7.73	1.943	-1.757	118.800	91.600	108.400	106.300	667.0	30000.0	1.30	F18
P00 757 806	7.95	1.454	-1.170	116.400	88.200	105.500	103.100	-2466.0	44700.0	1.40	F18
P00 810 806	8.17	3.848	-3.009	123.900	98.000	114.400	113.700	-8330.0	14200.0	1.10	F18
P001022 806	10.37	1.849	-1.849	119.300	94.200	108.800	108.200	-98.0	30000.0	1.30	F18
P001030 806	10.50	0.719	-0.674	111.200	76.500	98.700	92.600	0.0	0.0	0.00	
P001034 806	10.57	1.221	-0.963	114.800	87.200	103.800	101.300	983.0	45000.0	1.43	F18
P001043 806	10.72	4.024	-3.589	125.200	98.500	115.000	114.300	9977.0	16500.0	1.27	F14
P001048 806	10.80	5.912	-4.153	126.200	105.600	118.000	120.200	0.0	13000.0	1.10	F18
P001148 806	11.80	8.358	-5.339	128.700	107.600	120.500	122.800	-158.0	14000.0	1.20	F111D
P0012 4 806	12.07	1.473	-1.132	117.000	83.700	103.800	99.100	56.0	45000.0	1.40	F111D
P00 817 807	8.28	1.971	-1.442	117.900	85.600	106.600	102.000	0.0	0.0	0.00	
P0010 2 807	10.03	0.982	-1.158	115.400	83.900	102.300	98.300	0.0	0.0	0.00	
P001050 807	10.83	2.300	-1.964	121.000	97.700	109.400	111.000	-7803.0	29900.0	1.25	F111D
P01 841 800	8.68	3.216	-3.230	123.500	98.000	113.800	113.400	0.0	16000.0	1.20	F4
P01 748 803	7.80	2.246	-2.159	121.500	91.800	109.100	106.800	1287.0	29200.0	1.24	F4
P01 758 803	7.97	3.143	-2.657	123.200	96.100	112.500	111.500	3651.0	29300.0	1.29	F4

Table 3b - Augmented BOOMFILE Database (Rise Times)

FILE NAME	Time (Hrs)	Pmax (PSF)	Pmin (PSF)	t50 (ms)	t75 (ms)	t90 (ms)	t100 (ms)	Sideline (Feet)	Altitude (Feet)	Mach #	Aircraft
P00 841 800	8.68	3.491	-3.235	0.500	0.625	1.375	2.125	0.0	16000.0	1.20	F4
P00 748 803	7.80	2.682	-2.008	0.625	1.125	1.875	4.125	1387.0	29200.0	1.24	F4
P00 758 803	7.97	2.929	-2.722	0.250	0.375	1.125	4.875	3751.0	29300.0	1.29	F4
P001029 803	10.48	13.335	-3.232	6.875	7.000	6.750	7.625	-3358.0	14400.0	1.10	F4
P001043 803	10.72	1.764	-1.536	1.250	1.750	11.750	13.000	4754.0	44400.0	1.37	F4
P001238 803	12.63	0.726	-0.597	9.250	15.875	17.750	21.625	3717.0	21200.0	1.05	T38
P00 719 804	7.32	0.493	-0.453	2.500	3.750	5.500	7.750	-597.0	41400.0	1.17	AT38
P00 730 804	7.50	0.529	-0.672	2.125	4.875	6.750	11.500	1033.0	32300.0	1.12	AT38
P00 736 804	7.60	0.613	-0.646	2.000	4.250	8.250	11.000	7079.0	16700.0	1.15	AT38
P00 756 804	7.93	1.489	-1.095	0.500	1.125	1.375	2.250	8703.0	41400.0	1.38	F15
P00 756 804	7.93	0.207	-0.218	3.875	9.625	13.750	24.000	8703.0	41400.0	1.38	F15
P00 8 4 804	8.07	1.905	-1.496	0.875	1.125	1.125	5.250	2928.0	29700.0	1.20	F15
P00 810 804	8.17	3.507	-3.260	0.250	0.750	1.250	1.375	3679.0	12500.0	1.10	F15
P00 914 804	9.23	0.747	-0.817	0.500	1.750	3.750	6.250	-2003.0	38300.0	1.20	AT38
P00 923 804	9.38	1.160	-0.597	5.875	8.000	8.125	9.375	-2403.0	14000.0	1.10	AT38
P00 952 804	9.87	0.482	-0.399	0.875	2.625	7.125	10.250	0.0	0.0	0.00	
P001046 804	10.77	5.851	-3.044	0.250	0.375	0.750	0.875	4288.0	15200.0	1.13	F15
P0011 2 804	11.03	2.168	-1.571	1.875	2.500	2.250	3.125	-2853.0	31000.0	1.28	F15
P001111 804	11.18	0.982	-0.808	1.625	5.125	9.250	18.250	17103.0	45000.0	1.42	F15
P001134 804	11.57	1.924	-0.972	1.375	1.625	1.625	2.500	905.0	45500.0	1.40	F15
P001139 804	11.65	1.593	-1.071	7.125	19.500	19.375	23.625	0.0	0.0	0.00	
P00 820 805	8.33	0.895	-0.545	2.250	2.625	3.000	4.500	0.0	0.0	0.00	
P00 820 805	8.33	0.754	-0.648	2.500	3.500	4.250	5.750	0.0	0.0	0.00	
P00 9 6 805	9.10	1.081	-0.925	2.250	3.875	5.500	10.500	-10561.0	29500.0	1.25	F16
P00 9 6 805	9.10	0.705	-0.491	1.625	2.500	5.000	7.500	-10561.0	29500.0	1.25	F16
P00 926 805	9.43	1.205	-0.958	0.250	0.750	1.375	1.500	4226.0	64800.0	2.50	SR71
P00 933 805	9.55	0.879	-0.871	1.000	1.750	6.000	8.000	-2606.0	46700.0	1.43	F16
P00 944 805	9.73	2.809	-2.448	0.625	1.250	5.000	6.625	-5091.0	19300.0	1.17	F16
P001055 805	10.92	0.827	-0.698	1.500	3.875	8.375	20.500	0.0	73000.0	3.00	SR71
P0011 8 805	11.13	2.262	-1.773	0.375	3.250	3.625	4.000	-2986.0	32400.0	1.23	SR71
P001144 805	11.73	5.628	-3.328	3.625	4.000	4.125	5.000	-2119.0	14400.0	1.13	F16
P001154 805	11.90	3.772	-3.552	1.000	2.000	4.500	7.375	3264.0	13800.0	1.12	F16
P0012 4 805	12.07	1.900	-1.388	0.500	1.125	2.375	2.875	1993.0	30000.0	1.25	F16
P001235 805	12.58	1.330	-0.980	0.625	1.000	1.000	1.250	9995.0	52000.0	1.70	SR71
P00 744 806	7.73	1.943	-1.757	0.250	0.625	1.250	2.125	667.0	30000.0	1.30	F18
P00 757 806	7.95	1.454	-1.170	0.375	0.750	1.375	2.250	-2466.0	44700.0	1.40	F18
P00 810 806	8.17	3.848	-3.009	0.250	0.625	1.750	3.625	-8330.0	14200.0	1.10	F18
P001022 806	10.37	1.849	-1.849	0.250	0.375	0.625	1.250	-98.0	30000.0	1.30	F18
P001030 806	10.50	0.719	-0.674	1.125	2.625	3.750	6.125	0.0	0.0	0.00	
P001034 806	10.57	1.221	-0.963	0.375	0.500	0.875	3.375	983.0	45000.0	1.43	F18
P001043 806	10.72	4.024	-3.589	0.375	0.750	1.500	5.125	9977.0	16500.0	1.27	F14
P001048 806	10.80	5.912	-4.153	0.125	0.250	0.375	3.250	0.0	13000.0	1.10	F18
P001148 806	11.80	8.358	-5.339	0.250	0.500	0.750	1.250	-158.0	14000.0	1.20	F111D
P0012 4 806	12.07	1.473	-1.132	1.750	7.875	9.875	11.375	56.0	45000.0	1.40	F111D
P00 817 807	8.28	1.971	-1.442	2.500	3.875	5.375	6.125	0.0	0.0	0.00	
P0010 2 807	10.03	0.982	-1.158	0.500	1.000	3.125	5.250	0.0	0.0	0.00	
P001050 807	10.83	2.300	-1.964	0.250	0.375	0.500	0.625	-7803.0	29900.0	1.25	F111D
P01 841 800	8.68	3.216	-3.230	0.125	0.625	0.750	2.250	0.0	16000.0	1.20	F4
P01 748 803	7.80	2.246	-2.159	0.250	0.750	1.875	3.000	1287.0	29200.0	1.24	F4
[illegible] 803	7.97	3.143	-2.657	0.250	0.750	1.000	2.625	3651.0	29300.0	1.29	F4

Table 4a - BOOMFILE Data Analysis Groups

RANGE	GROUP 1	GROUP 2	GROUP 3	GROUP 4
Altitude (feet)	10,000 - 20,000	25,000 - 35,000	40,000 - 50,000	50,100 - 80,000
Mach number	1.05 - 1.30	1.10 - 1.40	1.10 - 1.50	1.50 - 3.50
Sideline Distance (feet)	0 - 45,000	0 - 55,000	0 - 80,000	0 - 60,000

Table 4b - XB-70 Data Analysis Groups

RANGE	GROUP 1	GROUP 2	GROUP 3	GROUP 4
Altitude (feet)	30,000 - 40,000	40,100 - 50,000	50,100 - 60,000	60,100 - 72,000
Mach number	1.17 - 1.55	1.17 - 1.87	1.55 - 2.31	2.05 - 2.92
Sideline Distance (feet)	0 - 50,000	0 - 80,000	0 - 70,000	0 - 80,000

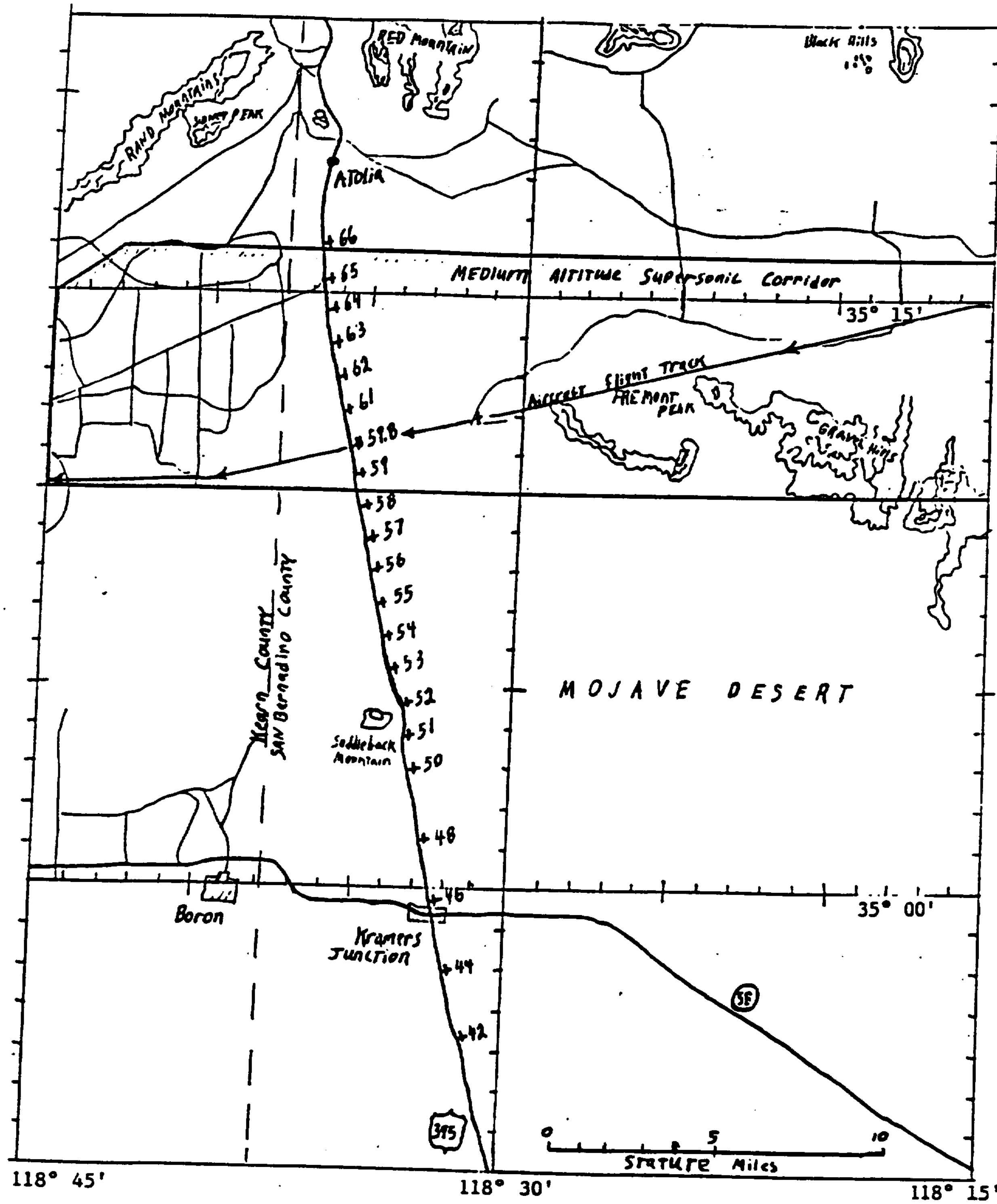


Figure 1 - BOOMFILE Test Site and Monitor Locations

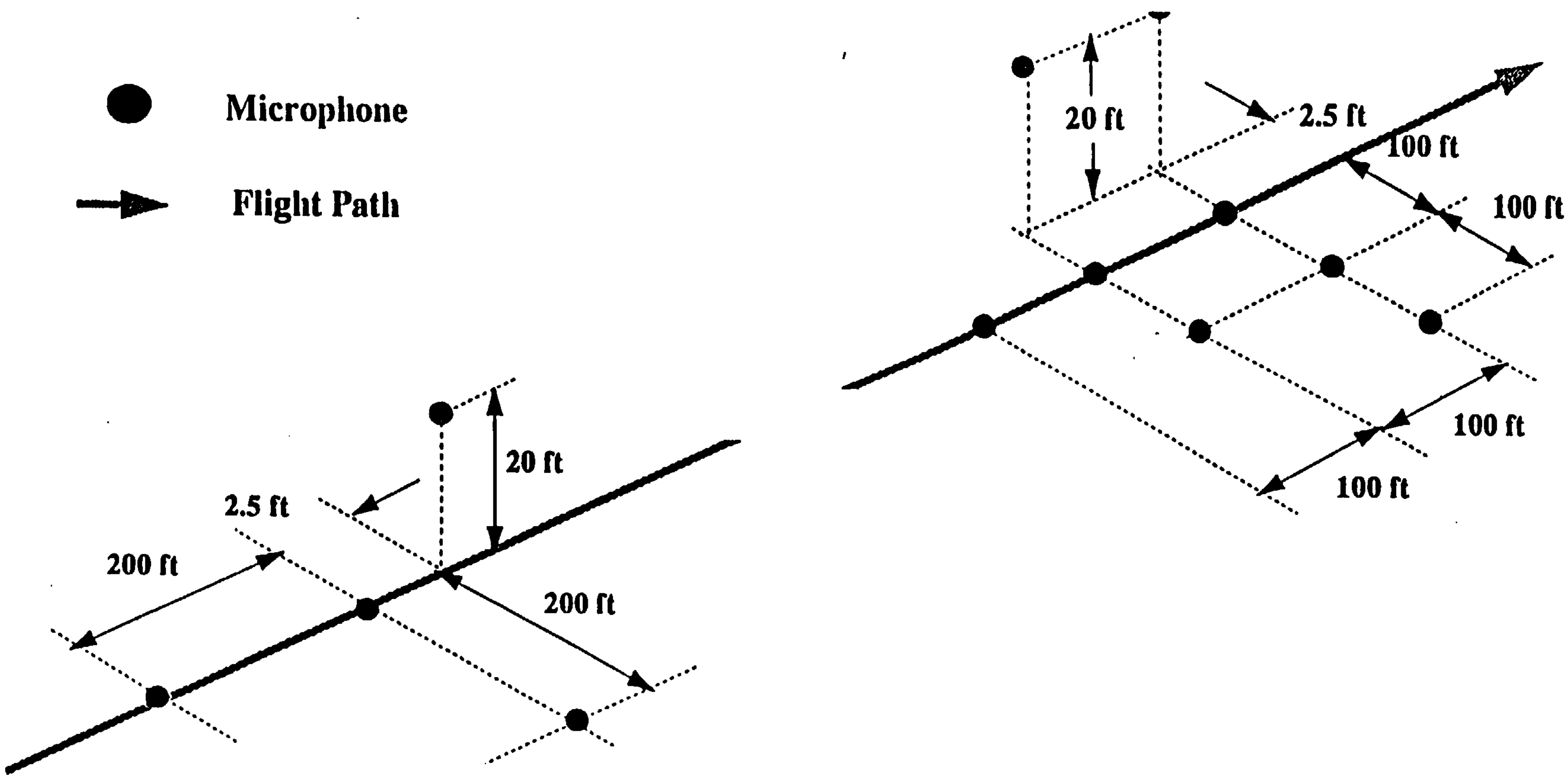
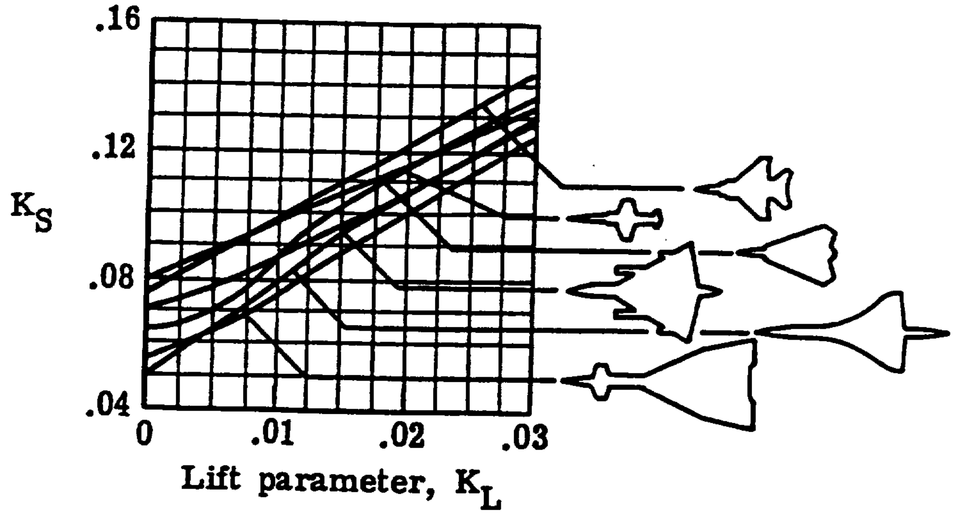


Figure 2 - XB-70 Sonic Boom Measurement Station Layouts



(1) Enter lift parameter K_L

$$K_L = \frac{\sqrt{M^2 - 1}\ W}{1.4 p_v M^2 l^2}$$

Select shape factor K_S

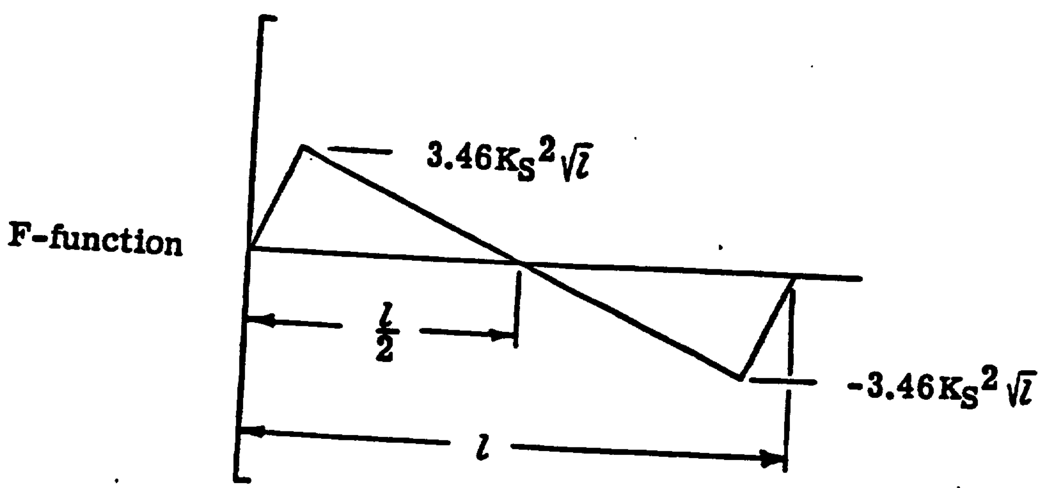


Figure 3 - Sonic Boom Prediction Procedure

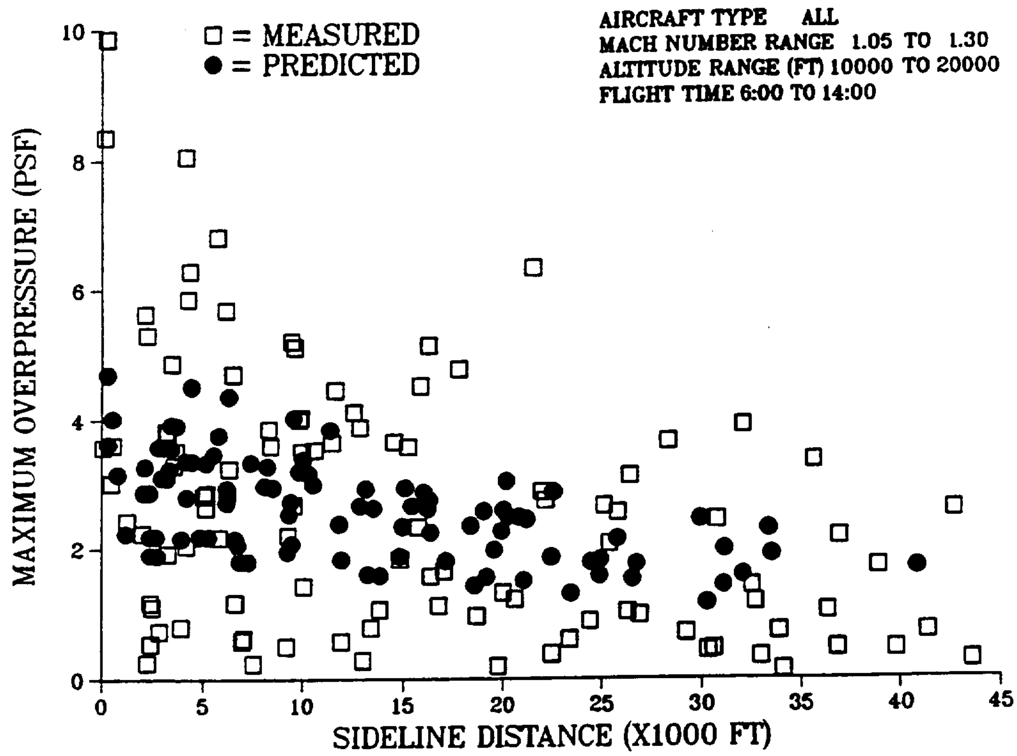


Figure 4a - BOOMFILE Overpressure Data (Low Altitude / Low Mach Number Group)

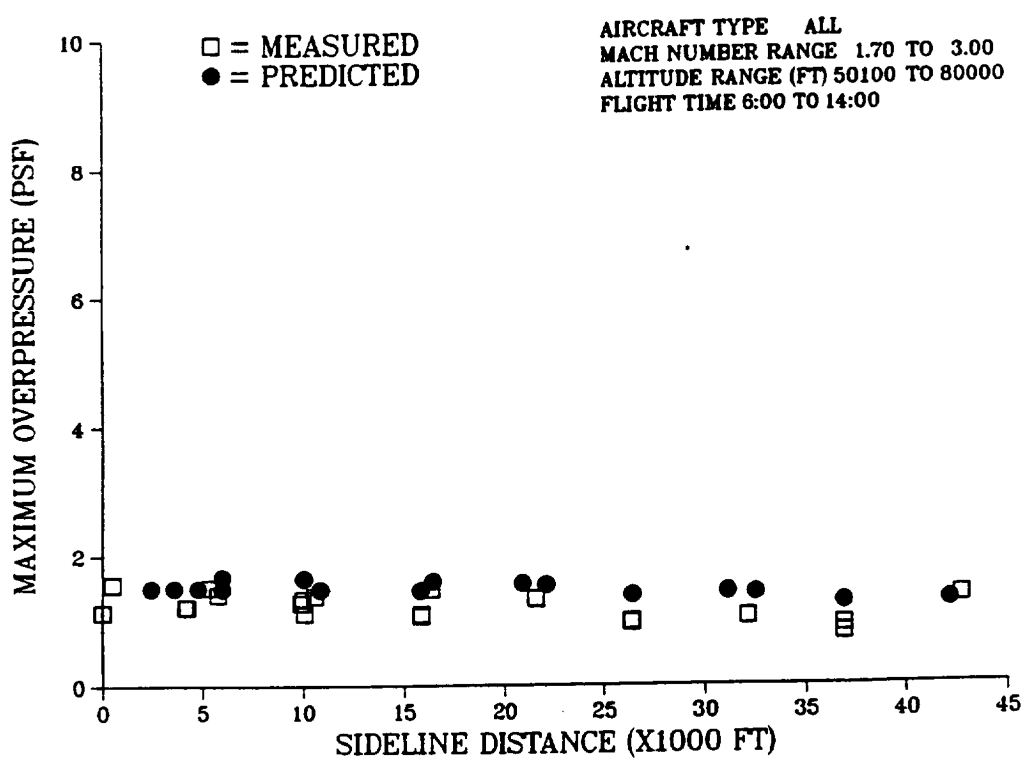


Figure 4b - BOOMFILE Overpressure Data (High Altitude / High Mach Number Group)

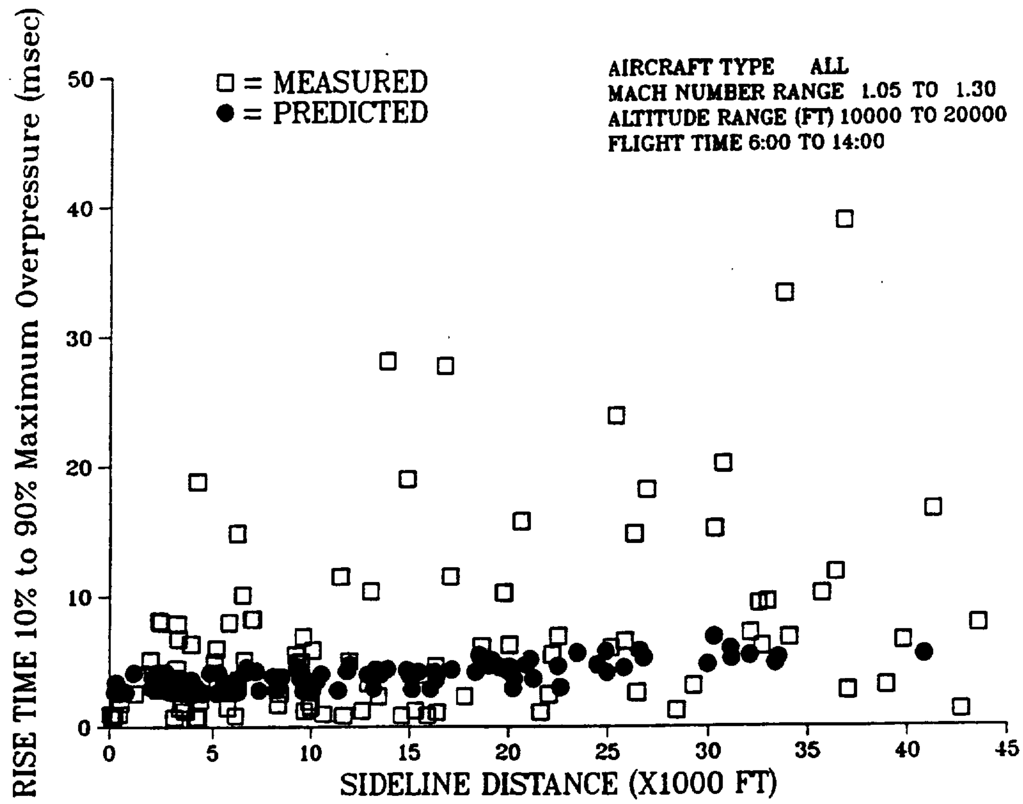


Figure 5a - BOOMFILE Rise Time Data (Low Altitude / Low Mach Number Group)

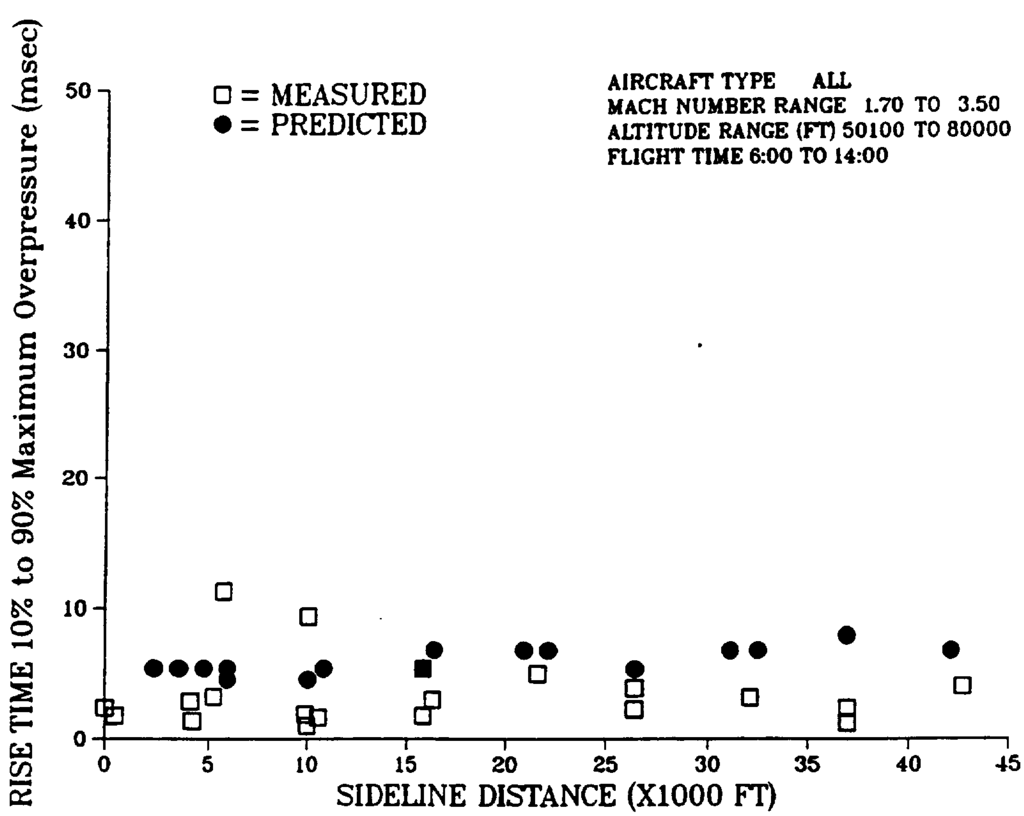


Figure 5b - BOOMFILE Rise Time Data (High Altitude / High Mach Number Group)

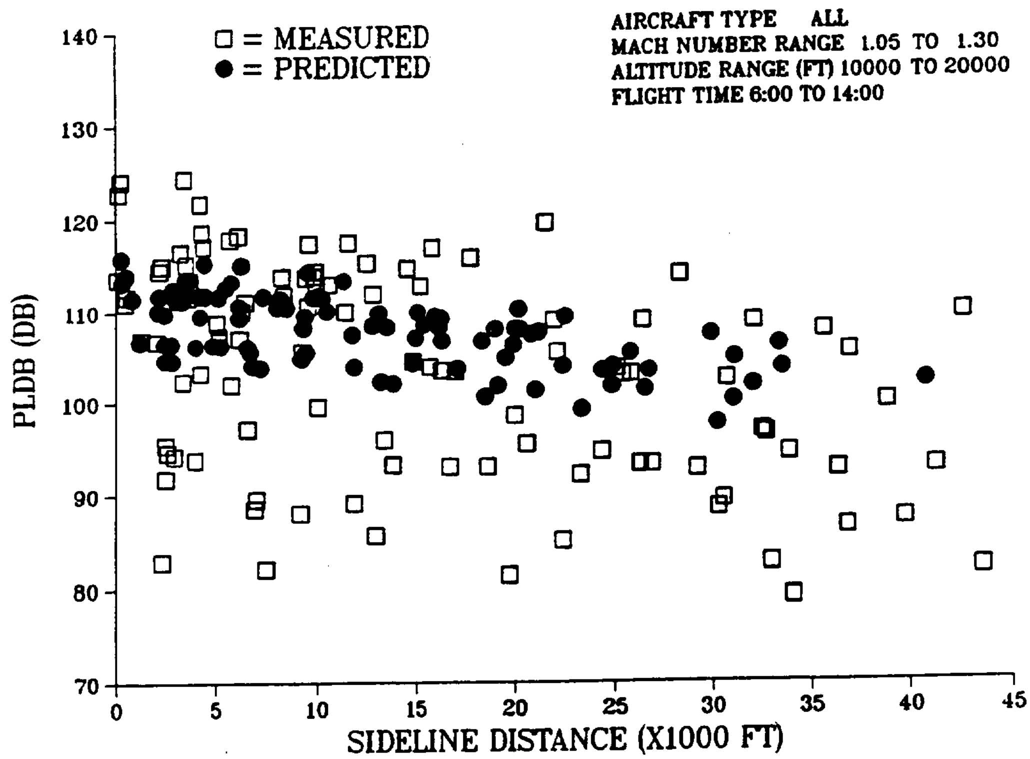


Figure 6a - BOOMFILE Loudness Level Data (Low Altitude / Low Mach Number Group)

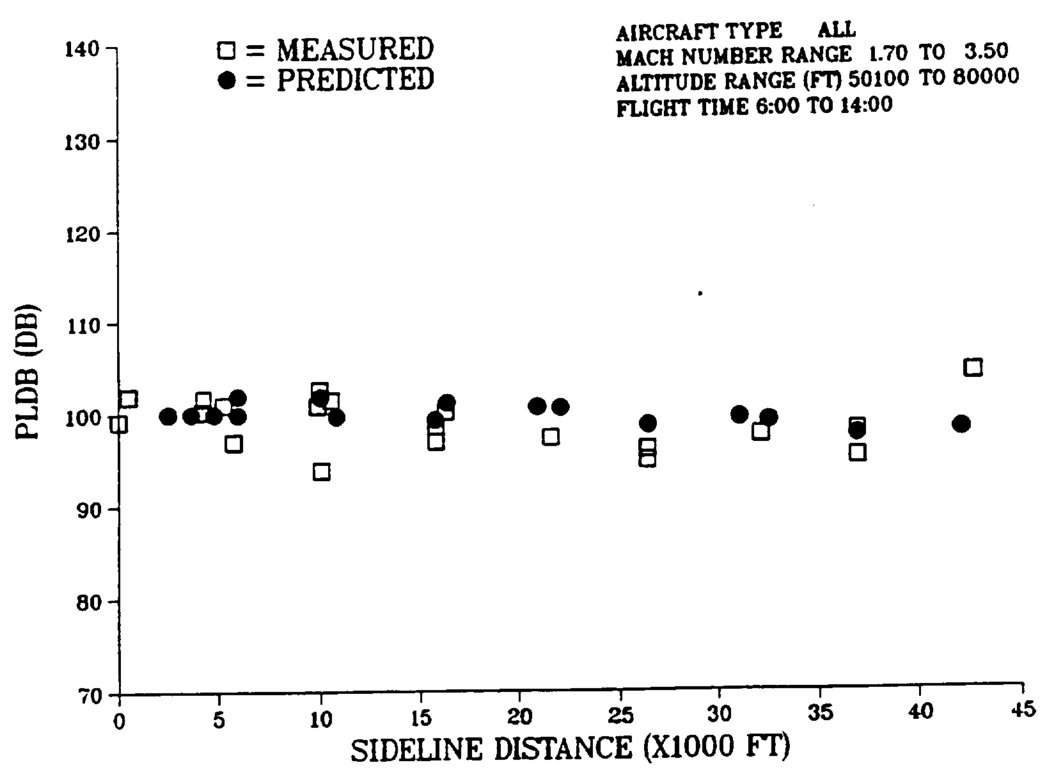


Figure 6b - BOOMFILE Loudness Level Data (High Altitude / High Mach Number Group)

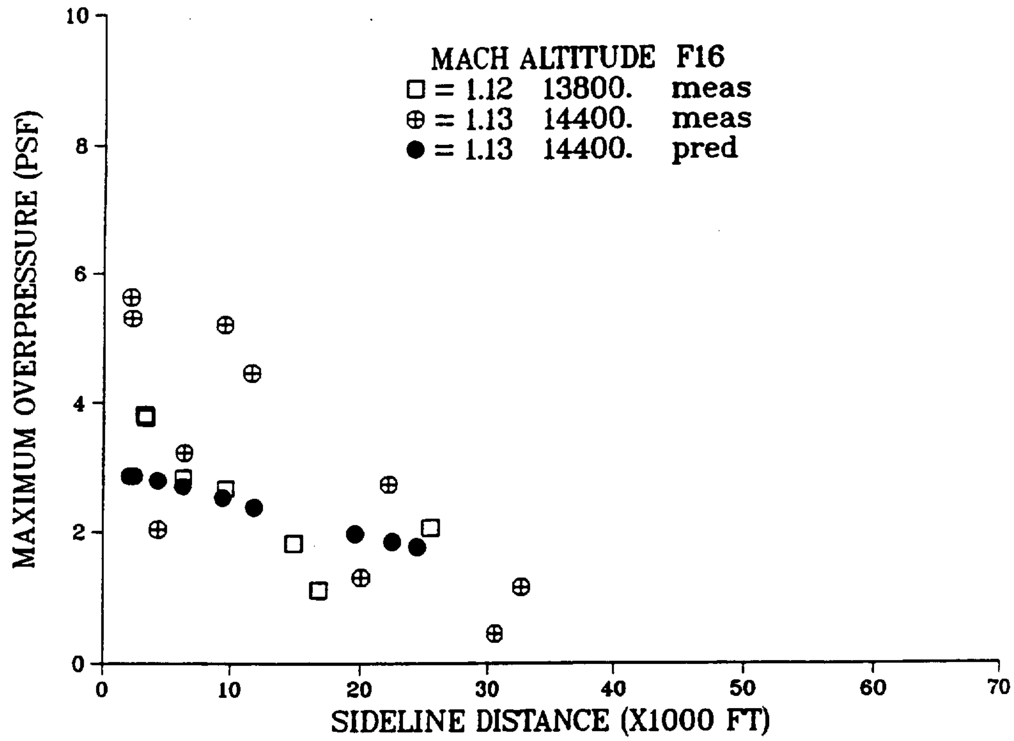


Figure 7a - BOOMFILE Overpressure (Repeat Flights of F16)

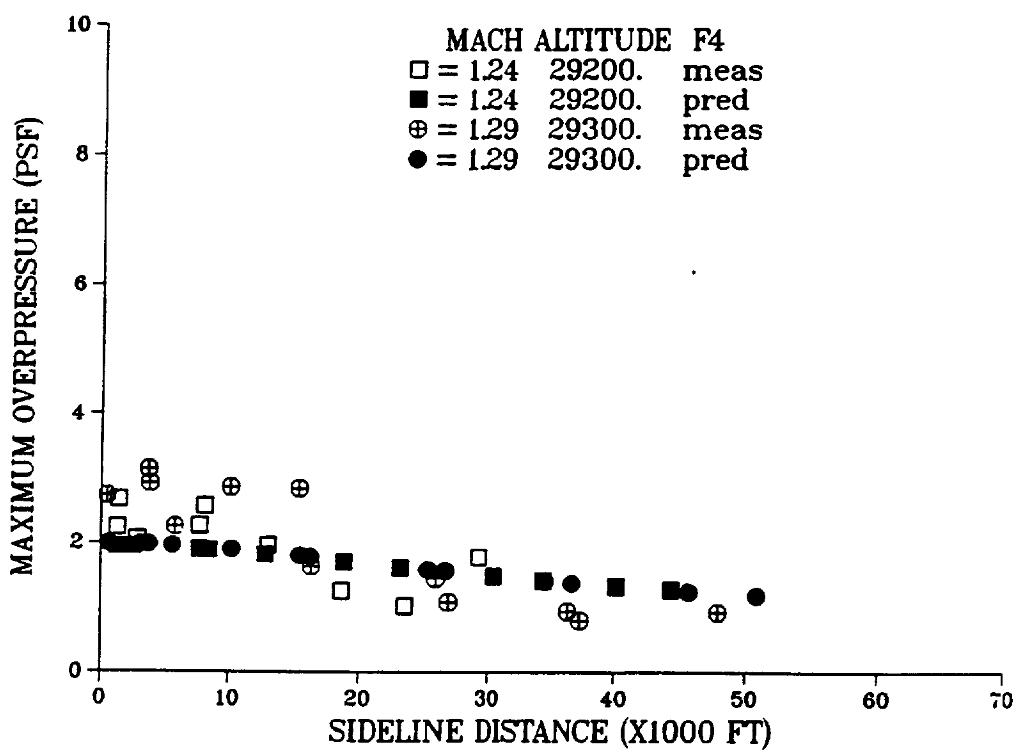


Figure 7b - BOOMFILE Overpressure (Repeat Flights of F4)

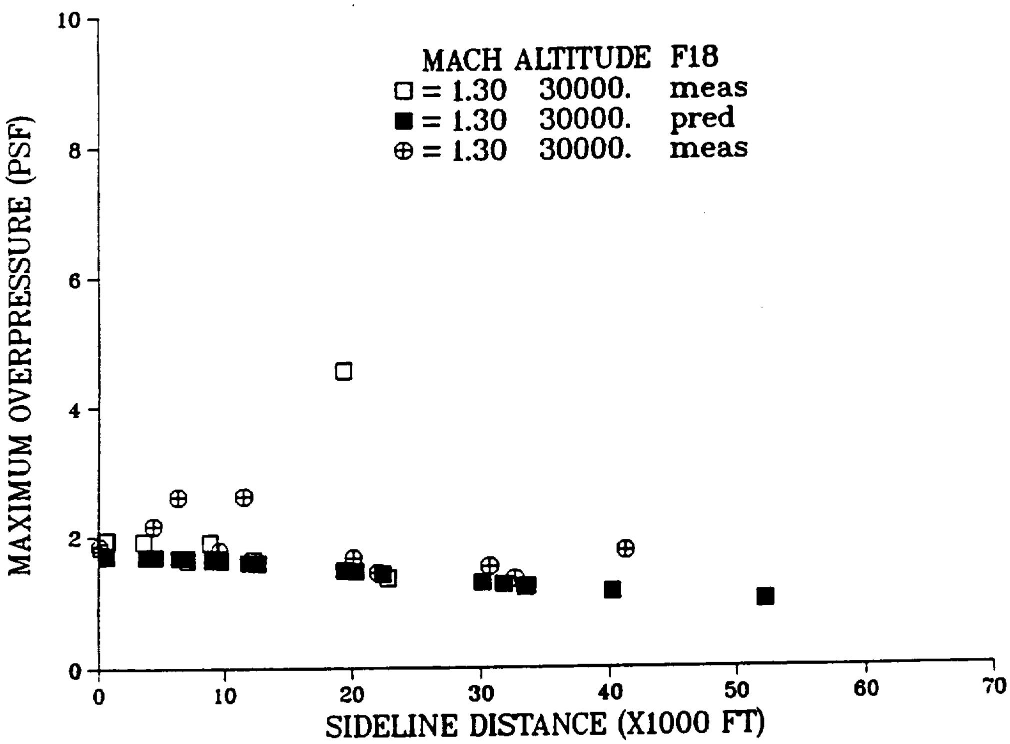


Figure 7c - BOOMFILE Overpressure (Repeat Flights of F18)

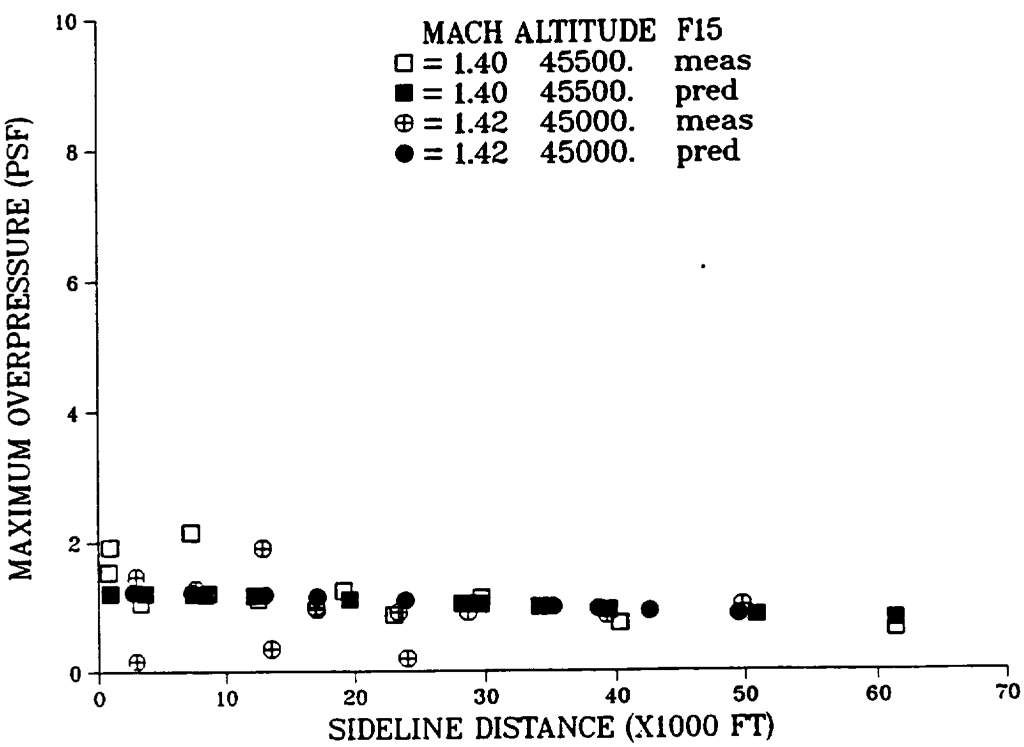


Figure 7d - BOOMFILE Overpressure (Repeat Flights of F15)

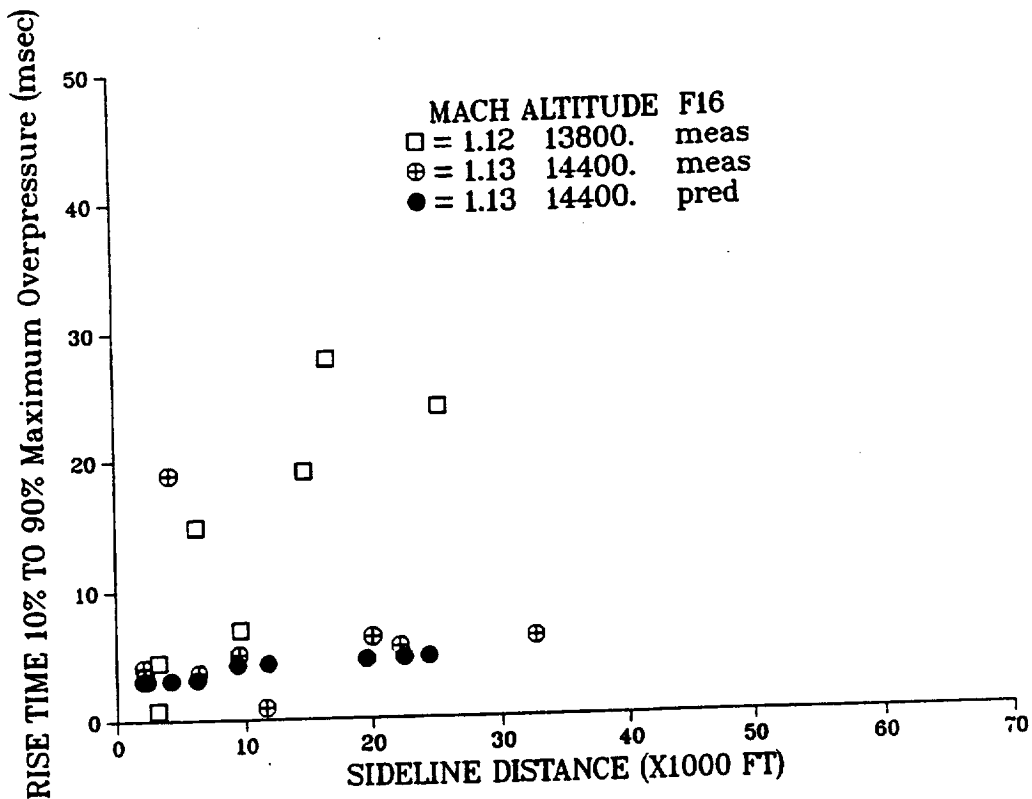


Figure 8a - BOOMFILE Rise Time (Repeat Flights of F16)

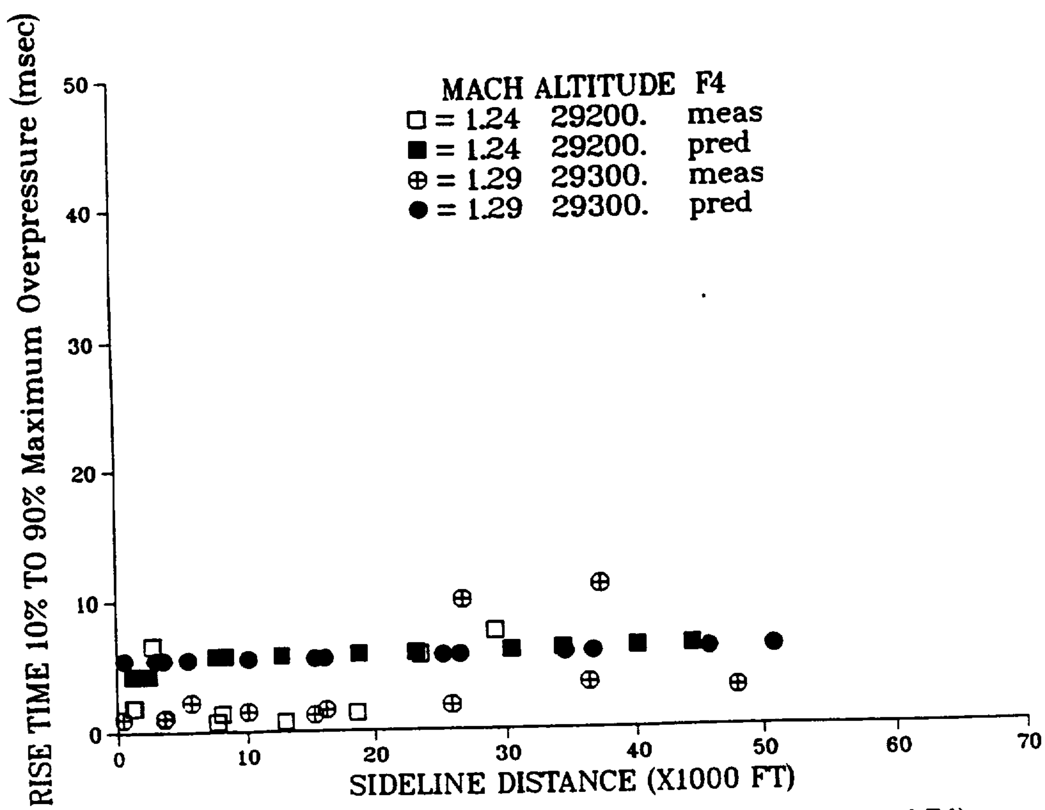


Figure 8b - BOOMFILE Rise Time (Repeat Flights of F4)

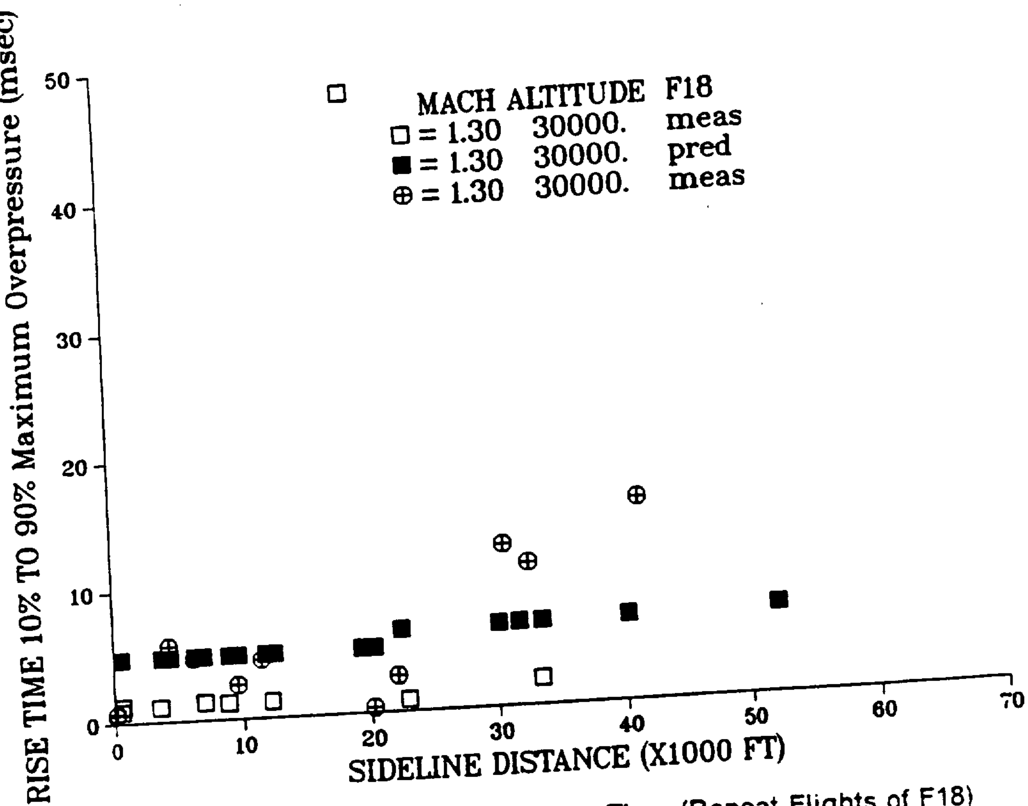


Figure 8c - BOOMFILE Rise Time (Repeat Flights of F18)

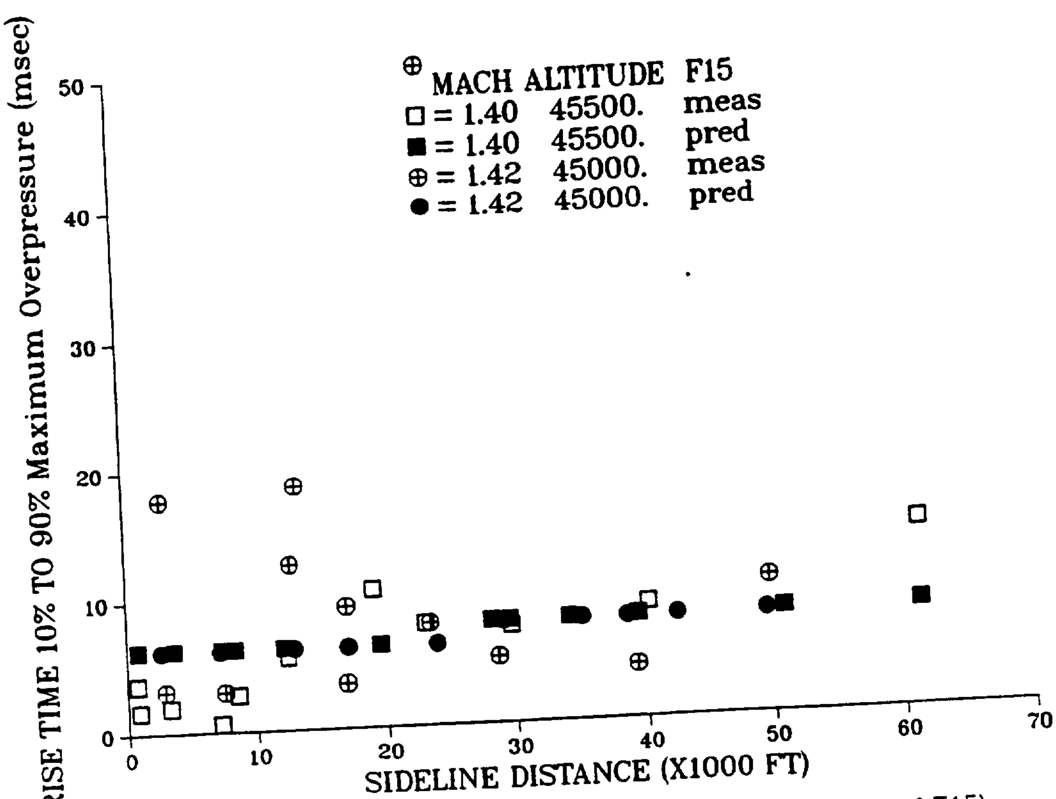


Figure 8d - BOOMFILE Rise Time (Repeat Flights of F15)

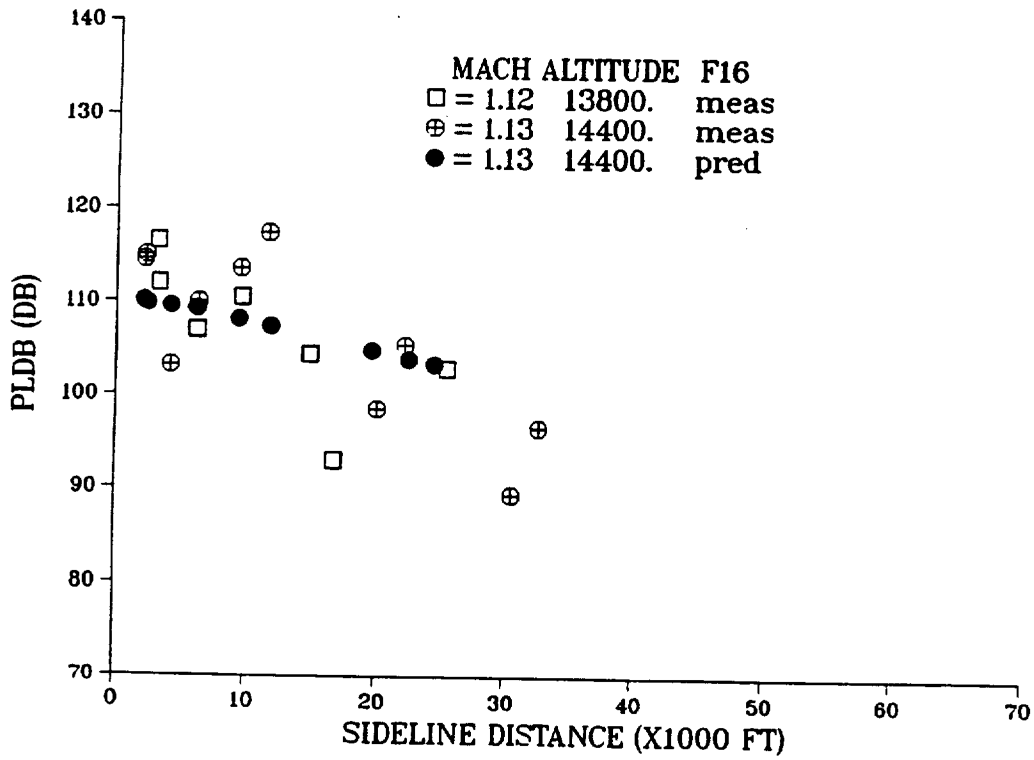


Figure 9a - BOOMFILE Loudness Level (Repeat Flights of F16)

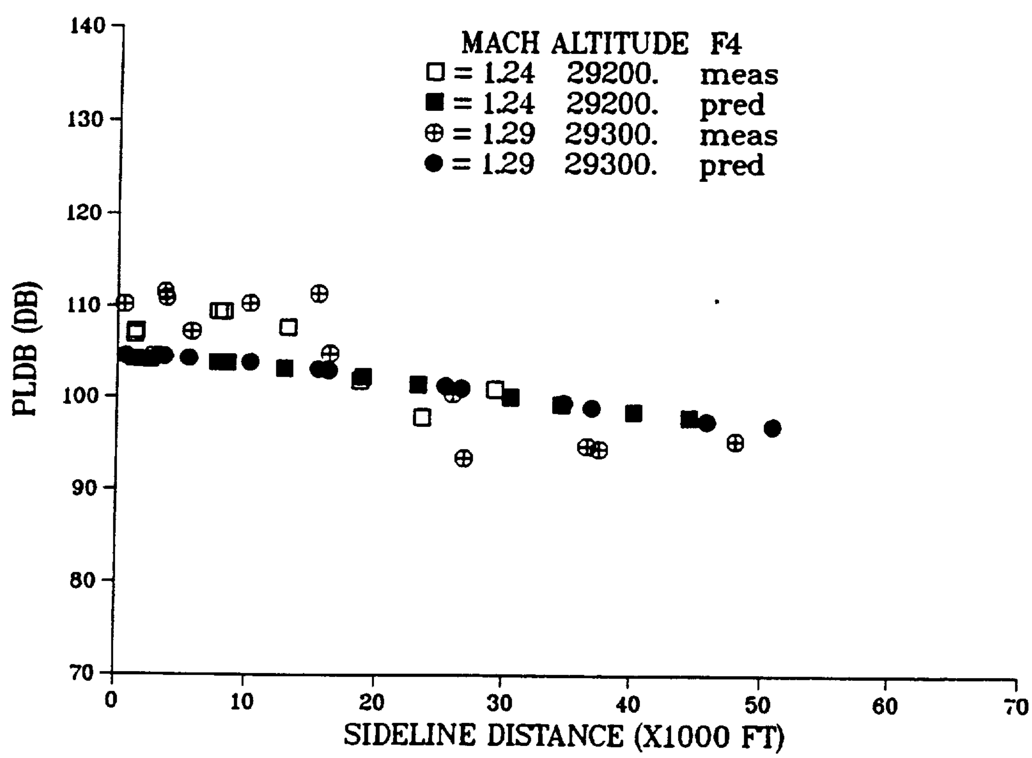


Figure 9b - BOOMFILE Loudness Level (Repeat Flights of F4)

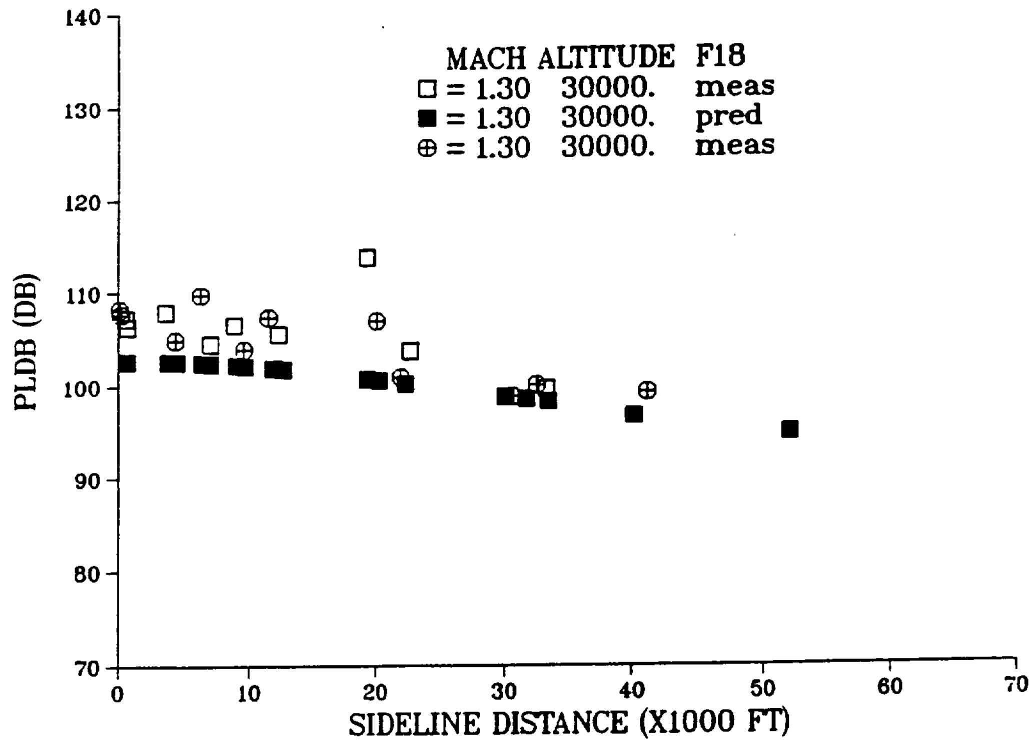


Figure 9c - BOOMFILE Loudness Level (Repeat Flights of F18)

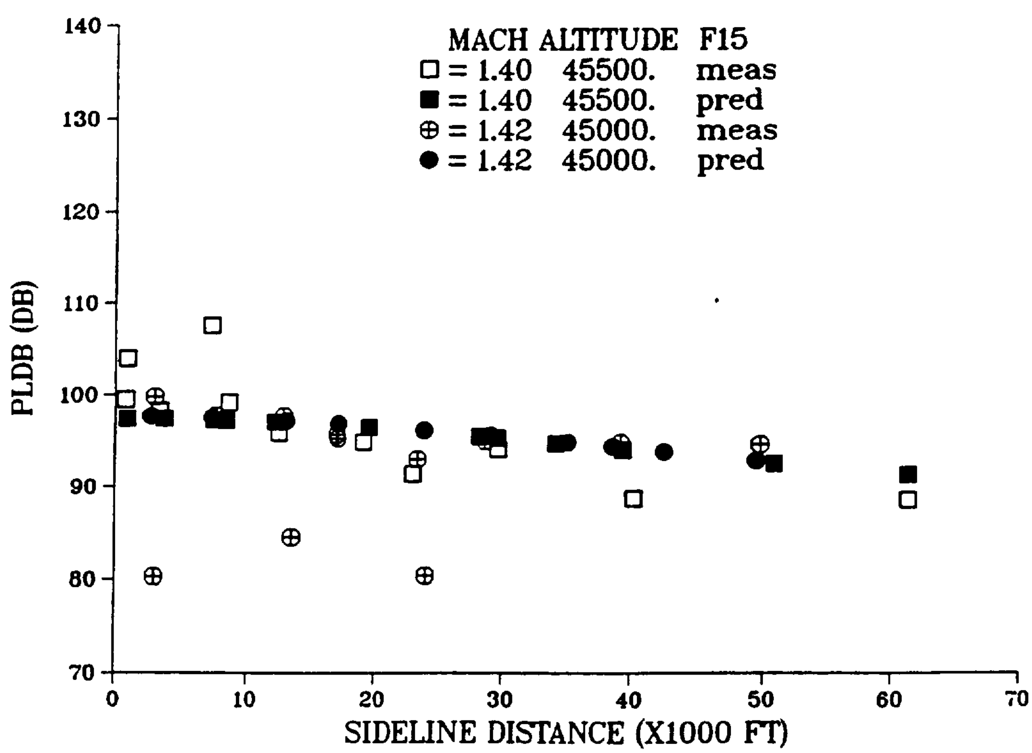


Figure 9d - BOOMFILE Loudness Level (Repeat Flights of F15)

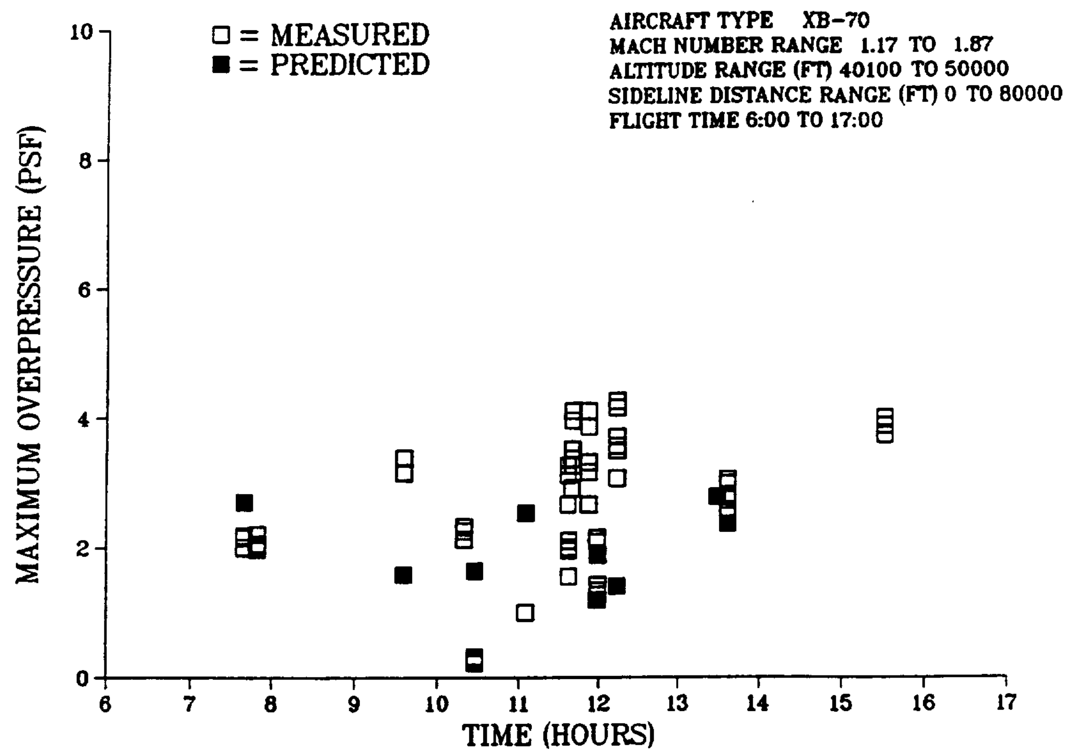


Figure 10a - XB-70 Overpressure Variation with Time of Day

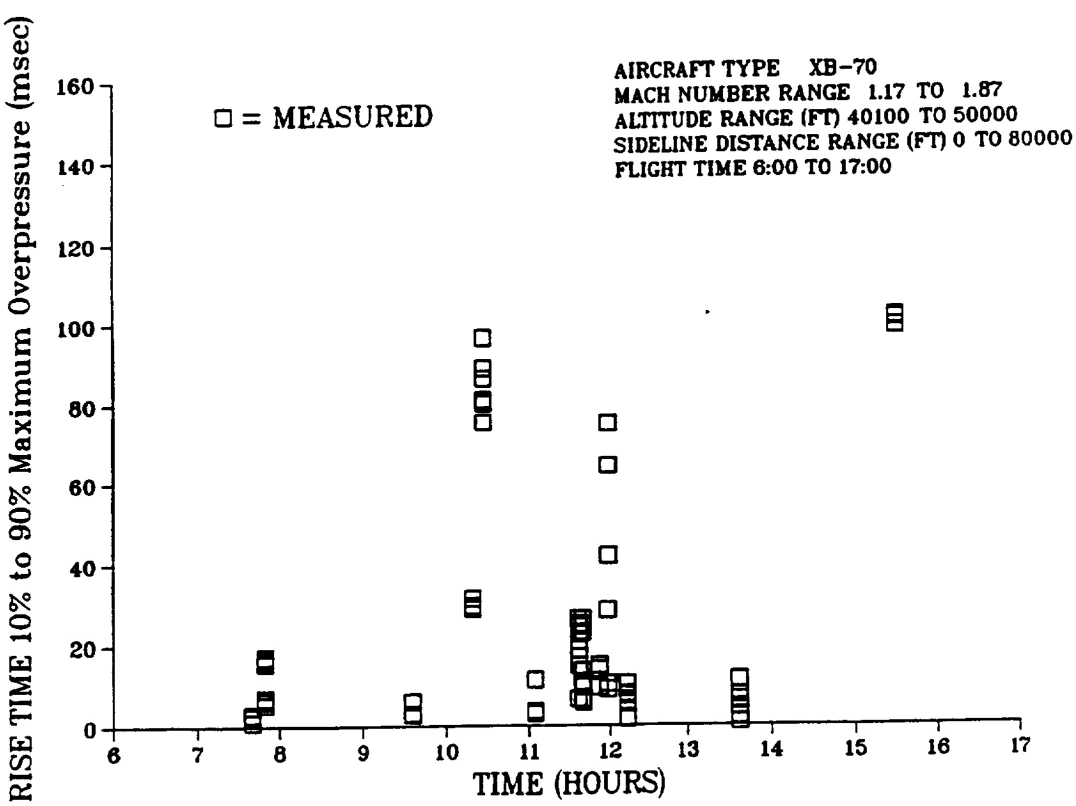


Figure 10b - XB-70 Rise Time Variation with Time of Day

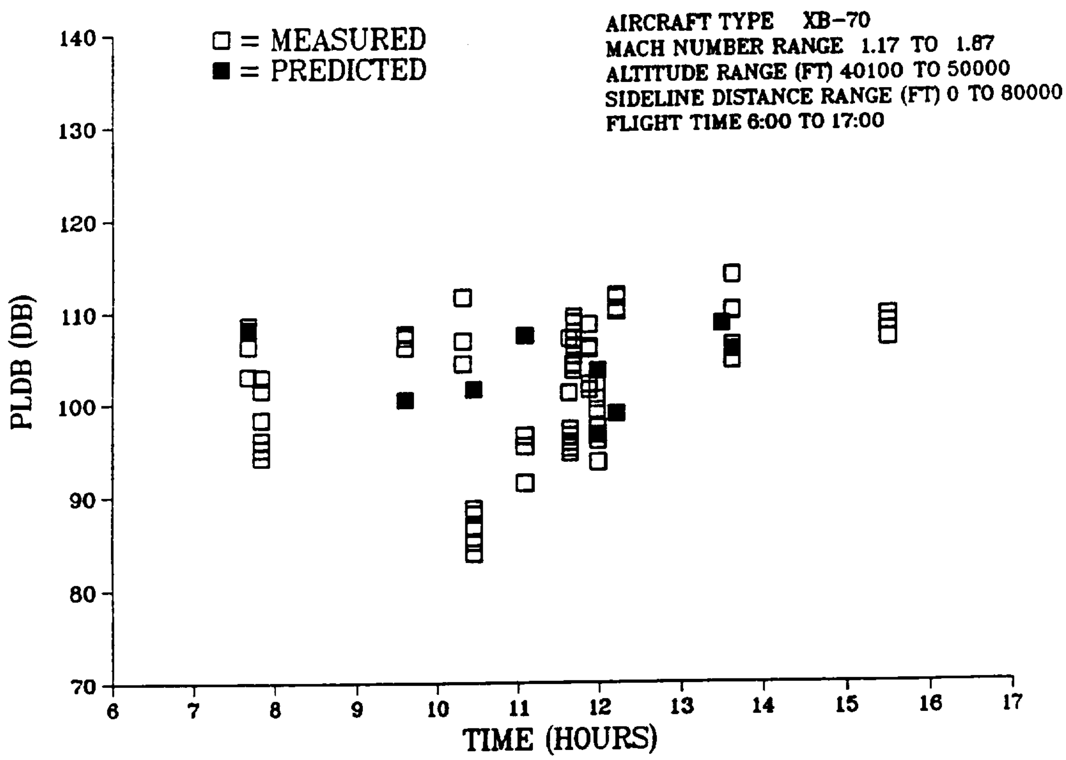


Figure 10c - XB-70 Loudness Level Variation with Time of Day

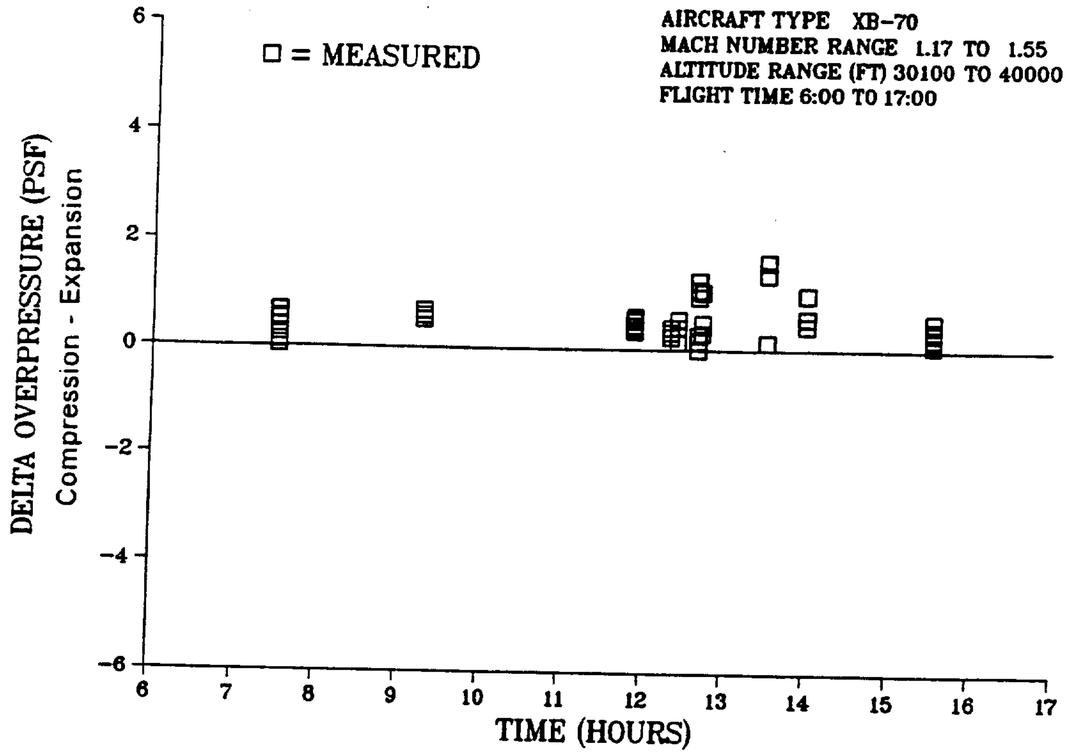


Figure 11a - XB-70 Overpressure Asymmetry (Low Altitude / Low Mach Number Group)

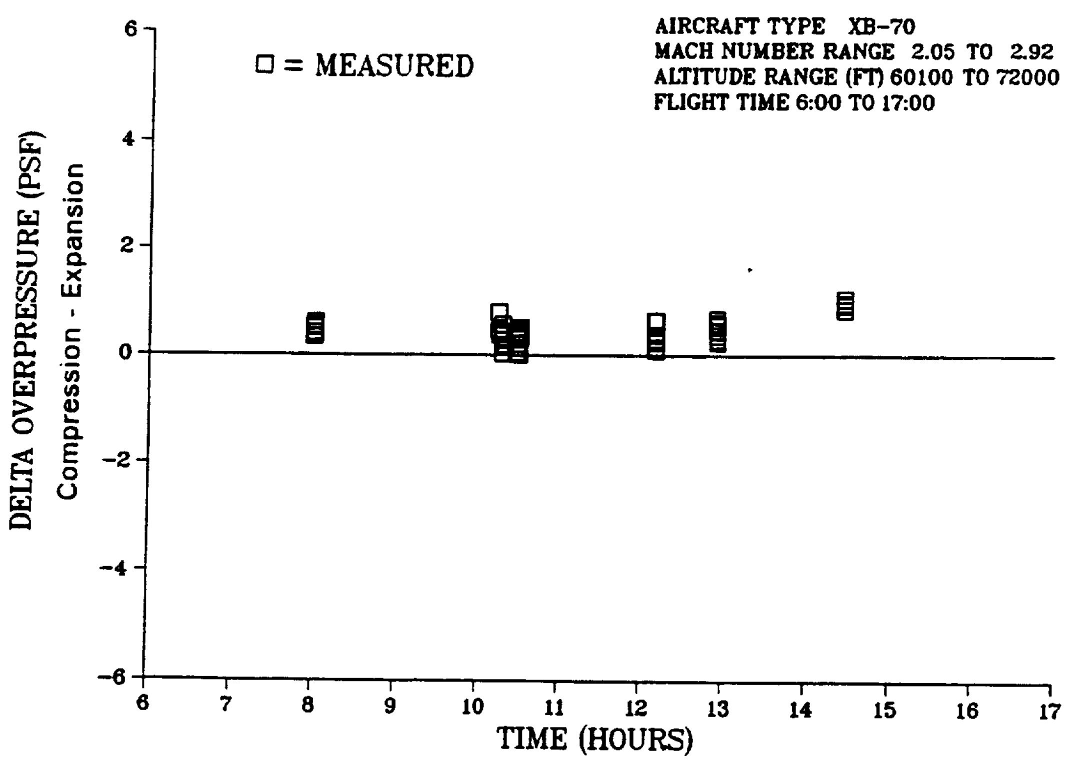


Figure 11b - XB-70 Overpressure Asymmetry (High Altitude / High Mach Number Group)

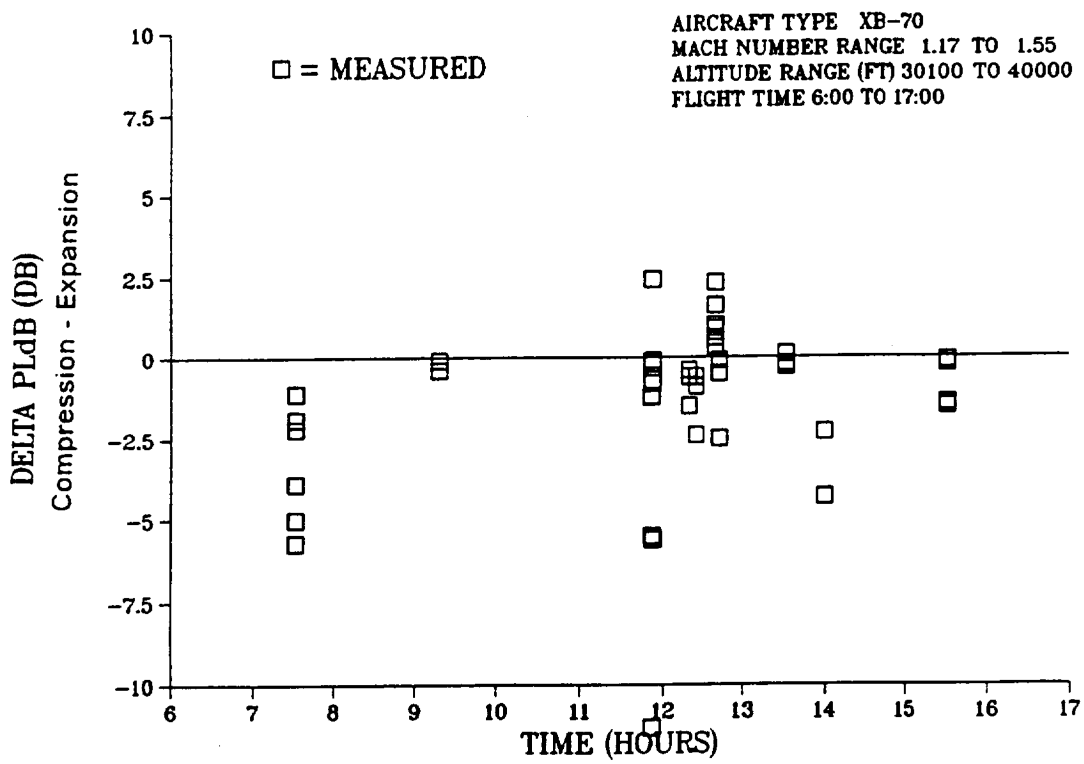


Figure 12a - XB-70 Loudness Level Asymmetry (Low Altitude / Low Mach Number Group)

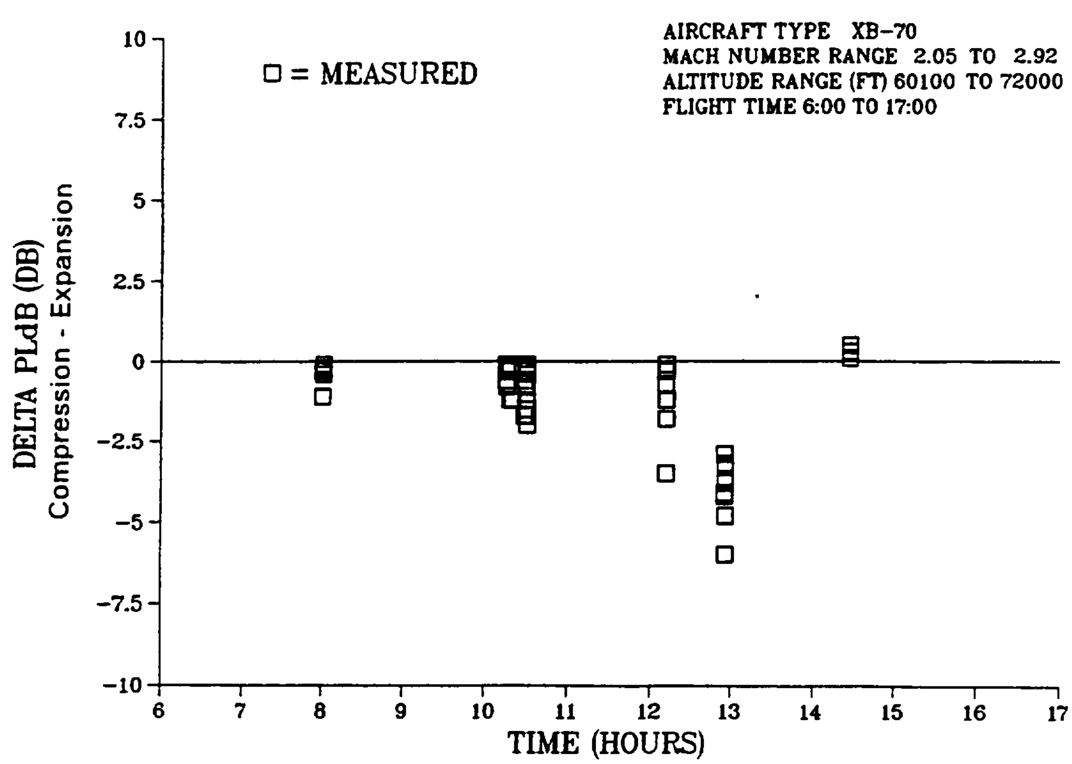


Figure 12b - XB-70 Loudness Level Asymmetry (High Altitude / High Mach Number Group)

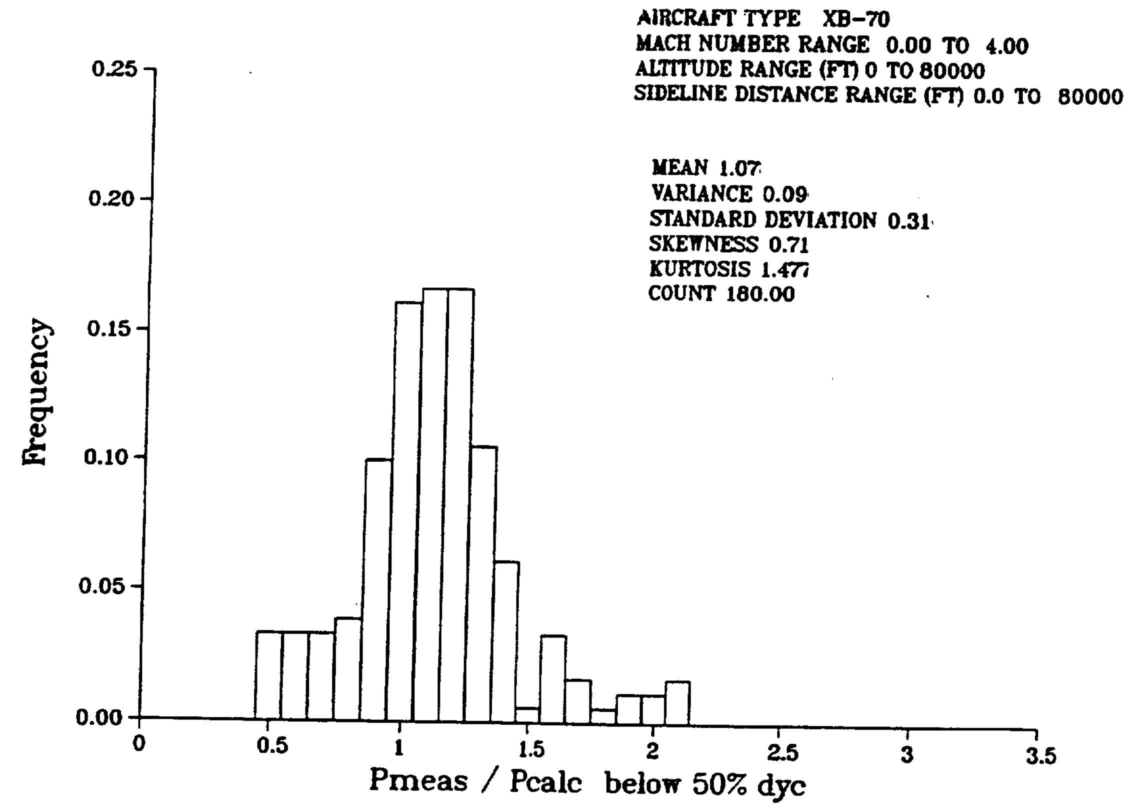


Figure 13a - XB-70 Normalized Overpressure Distribution
(Lateral Distances Less Than 50% of Cutoff)

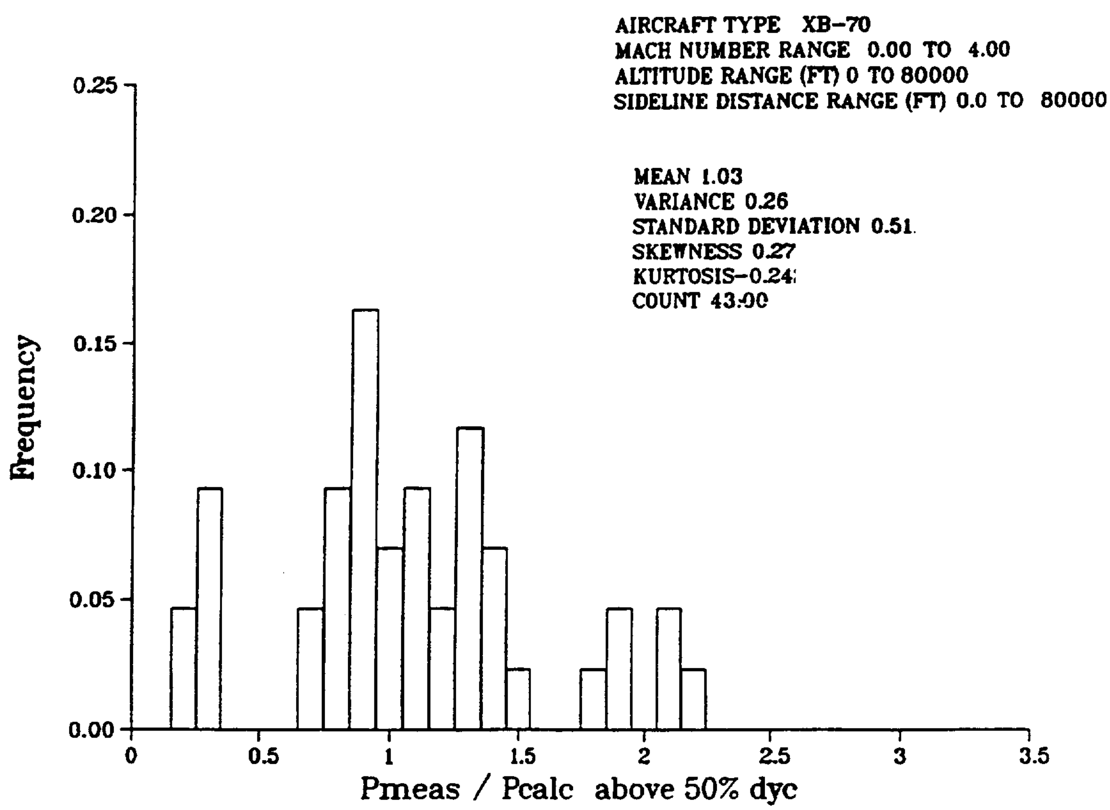


Figure 13b - XB-70 Normalized Overpressure Distribution
(Lateral Distances Greater Than 50% of Cutoff)

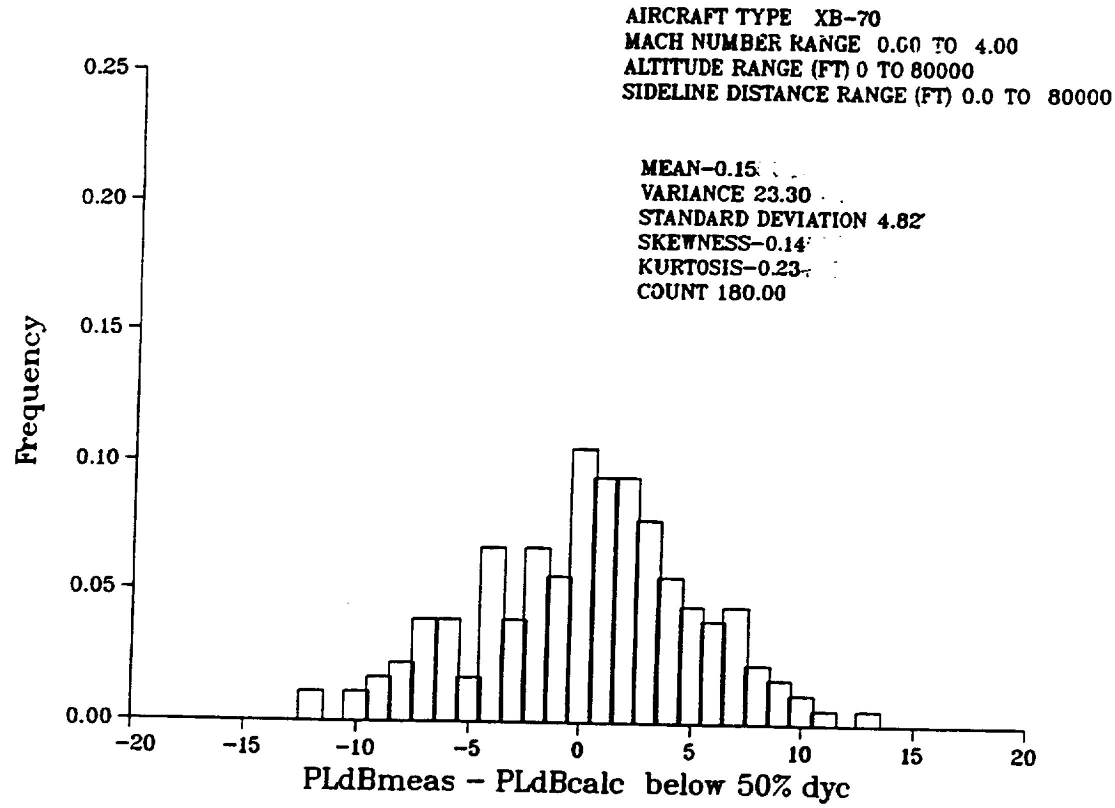


Figure 14a - XB-70 Adjusted Loudness Level Distribution

(Lateral Distances Less Than 50% of Cutoff)

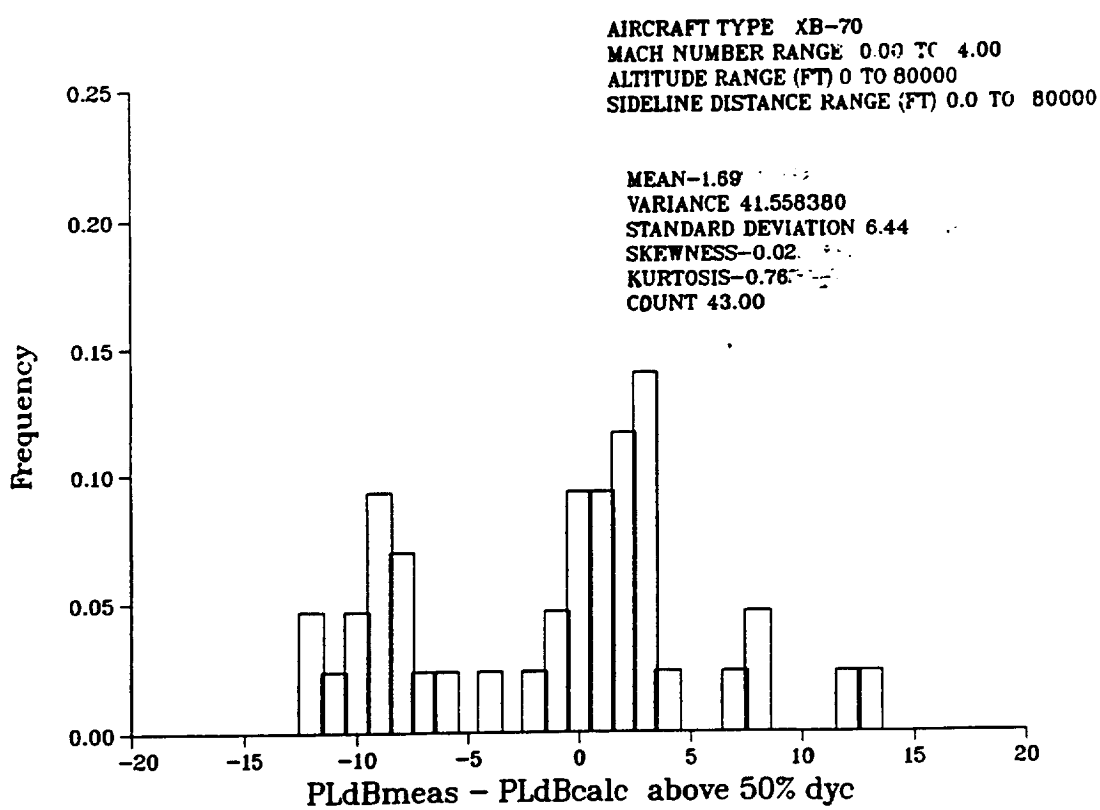


Figure 14b - XB-70 Adjusted Loudness Level Distribution

(Lateral Distances Greater Than 50% of Cutoff)

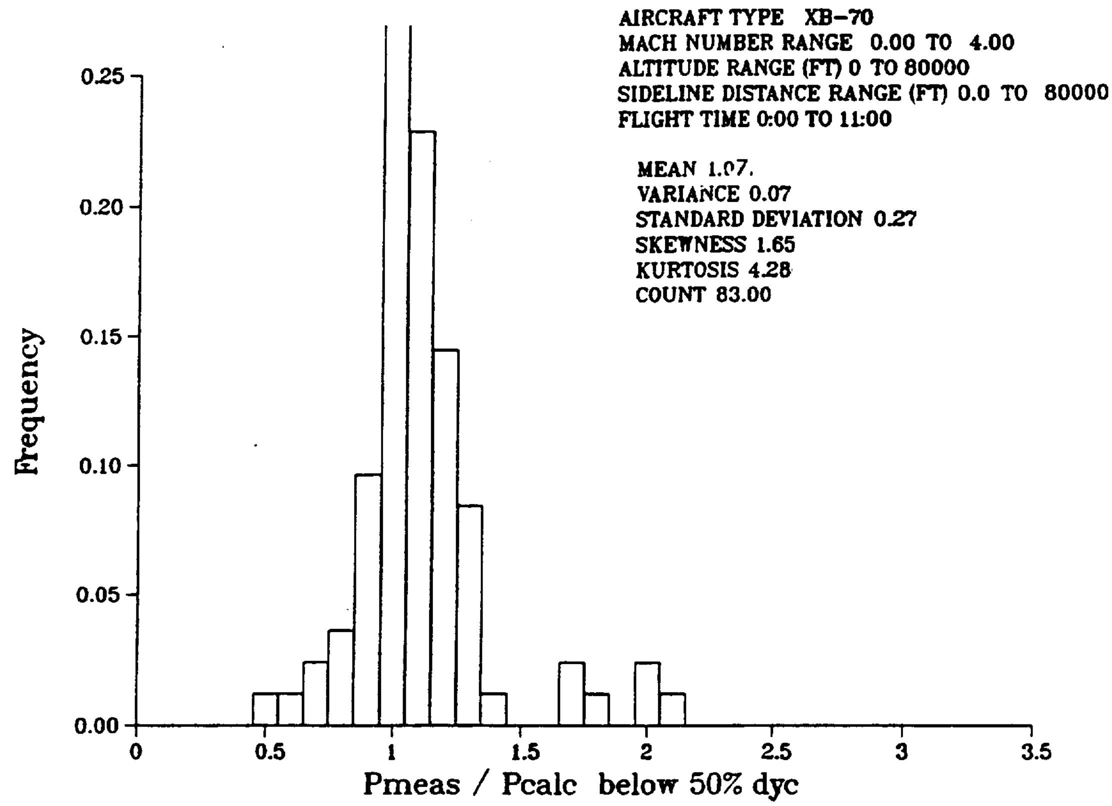


Figure 15a - XB-70 Normalized Overpressure Distribution (Morning Hours)

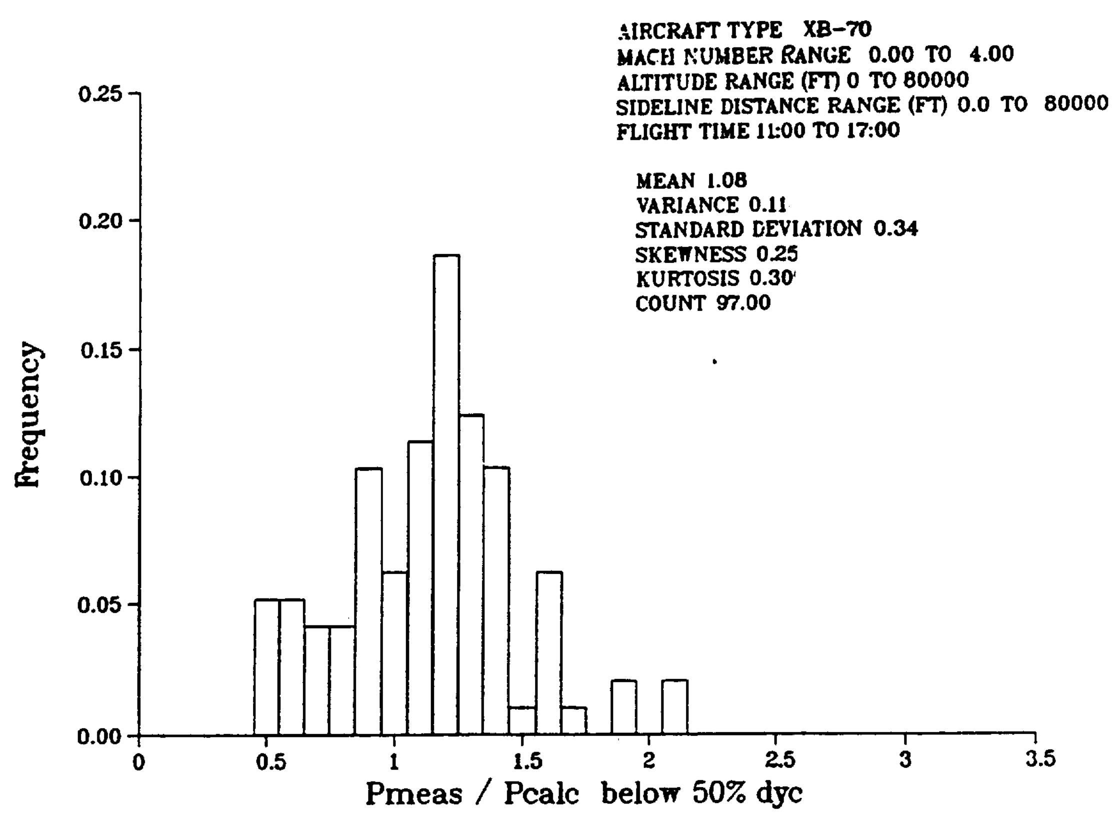


Figure 15b - XB-70 Normalized Overpressure Distribution (Afternoon Hours)

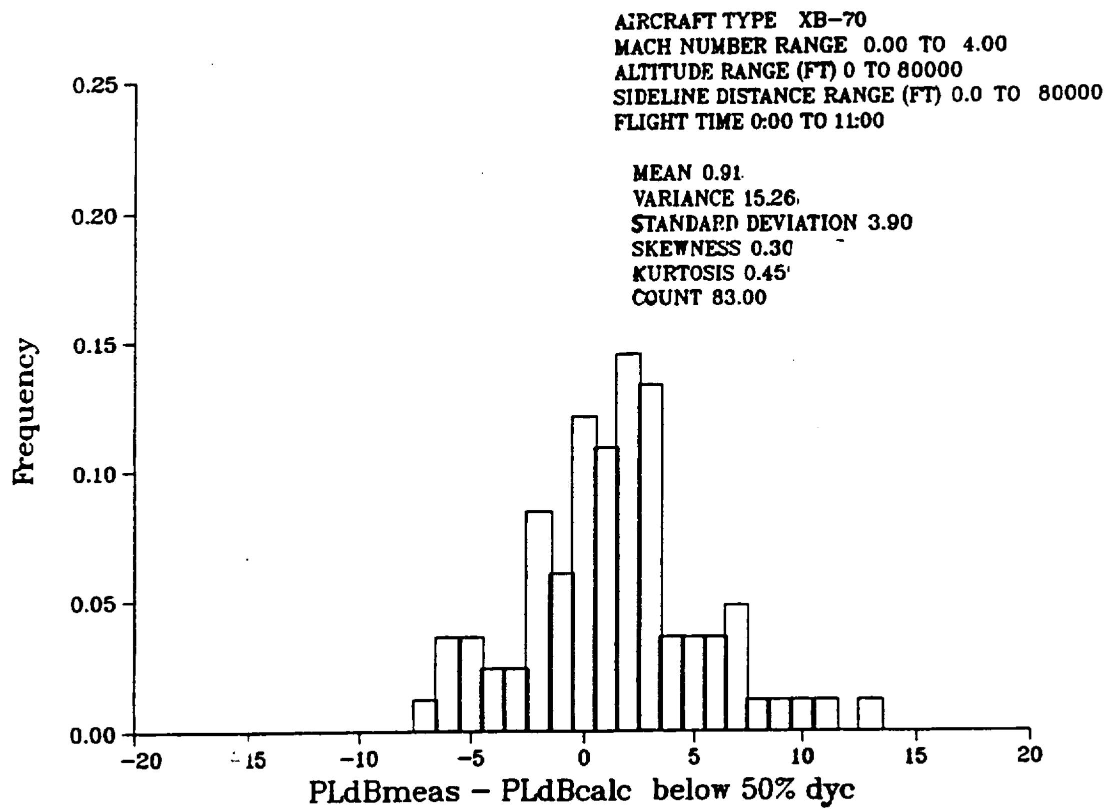


Figure 16a - XB-70 Adjusted Loudness Level Distribution (Morning Hours)

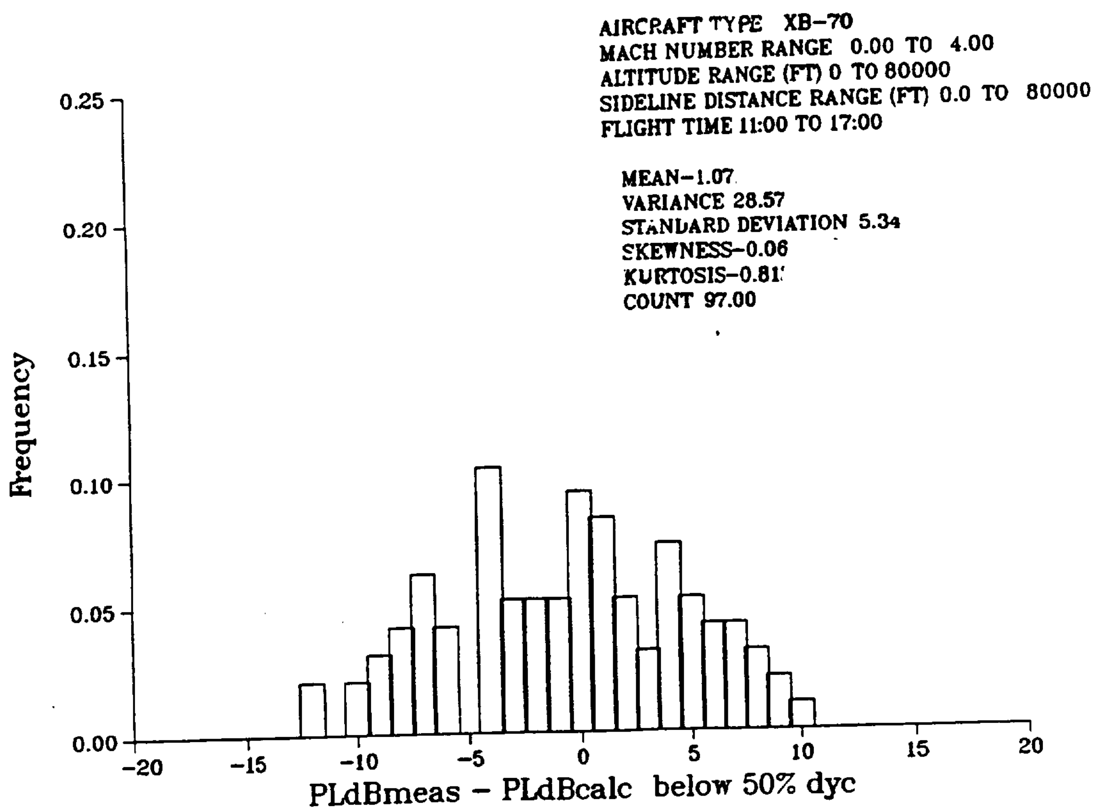


Figure 16b - XB-70 Adjusted Loudness Level Distribution (Afternoon Hours)

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13. ABSTRACT *(Maximum 200 words)*

Sonic boom signatures from two databases - the BOOMFILE and the XB-70 were analyzed in terms of C-weighted sound exposure level (CSEL), A-weighted sound exposure level (ASEL), and Stevens Mark VII perceived level (PLdB), as well as the more traditional peak positive overpressure and rise time. The variability of these parameters due to propagation through atmosphere was analyzed for different aircraft Mach number and altitude groups.

The low Mach number / low altitude group had significantly greater variation in rise time, overpressure, and loudness level than the high Mach number / high altitude group. The loudness of measured booms were found to have a variation of up to 25 dB relative to the loudness of boom predicted for a non-turbulent atmosphere. This is due primarily to the steeper ray paths of the high Mach number / high altitude group and the corresponding shorter distances traveled by these rays through the lower atmosphere resulting in reduced refraction effects. The general trend of decreased overpressure and loudness level with increasing lateral distance was also seen. Sonic boom signatures from early morning flights had less variation in rise time and overpressure than afternoon flights because of reduced turbulence. Measures of asymmetry (difference between compression and expansion portion of the signature) showed that the variability in Δ loudness level was greater than the variability in Δ overpressure due to the large influence of turbulence on rise time. Lastly, analysis of data within 50% of lateral cutoff showed that the mean value for overpressure and loudness level was independent of time of day but that the frequency with which it occurred was greater in the morning. This is a clear indicator of increased turbulence in the afternoon..

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